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DIASTROPHISM AND THE FORMATIVE PROCESSES

XV. THE SELF-COMPRESSION OF THE EARTH AS A PROBLEM OF ENERGY

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The discoveries of the last three decades have led to new views of the constitution of matter, new evaluations of cosmic energy, new estimates of evolutionary rates, and new concepts of the time factor generally. Nearly all the fundamental concepts of geology need some degree of revision in the light of these radical advances. Among the rest there is need to rectify the concept of the earth's compression.

THE CONCEPT OF COMPRESSION IN THE LIGHT OF NEW CONCEPTS OF MATTER

So long as matter was supposed to be formed of minute irreducible atoms, it was logical to assume that when these atoms were pressed into contact there was an end of compression. It was also quite natural to build upon this mechanical concept a merely mechanical notion of the process of compression. The new discoveries, however, lead to the view that the atom is a highly dynamic organization, a complex revolutional system, carrying within itself prodigious stores of energy and a structure as open as a planetary system. The materialistic factors—if

indeed they are really materialistic at all—recede to minute points, and do little more than play the part of carriers of electric charges. The prodigious energies of the atoms seem to be stored in the extremely rapid revolutions of these charged integers and in the fields of force and the polarities which arise from them. The atom itself and all the combinations into which it enters are therefore to be regarded as theoretically compressible to an undefined degree. The old assigned limit vanishes, and no new one takes its place. For aught that is now known, even the nuclei, or protons, and the electrons may themselves be composite dynamical organizations and subject to compression. The fact that a nucleus has a mass 1,800 times that of an electron suggests that perhaps analysis has yet one or more steps at least to take. Compression is therefore to be pictured as the struggle of one phase, or one set of phases, of energy against another phase, or set of phases, of energy, both sets being embodied in motion.

While perhaps it cannot yet be said to be strictly proved that the positive and negative charges are in revolution about one another, there seems to be no other way in which the prodigious energies associated with them can be stored without giving such evidences of themselves as characterize the non-revolutionary activities, distinctions to be considered later. Moreover, the notable successes of the revolutional hypotheses in accounting for observed phenomena leave little room for doubt that they are substantially true, and may be taken as a fairly safe working-basis.

In addition to the evidences of the atoms themselves, the analogies of the larger units of the cosmos lend support to the view that the atoms are revolutionary organizations.

THE CONTRASTED MANIFESTATIONS OF ENERGY

In the great stellar field, where the largeness of things makes visualization easier than in the hidden ultra-microscopic world within, energy manifests itself in two rather distinct kinds of activity. The one is continuous motion in cyclic orbits or spiraloid revolutions running on indefinitely without loss of energy. It is, therefore, conservative and singularly undemonstrative. In the other, the motion is habitually interrupted by reversals and so is

discontinuous and disjunctive, giving rise to diversions and scatterings of energy in oscillatory radiations. This vibratory phase of activity is at once dissipative, agitative, and demonstrative. It has a general destructive tendency, while cyclic motion has a general constructive tendency. However, by weakening old structures, vibratory action prepares the way for new construction. The two types are therefore co-operative as well as antagonistic. The vibratory type has its chief manifestation in the heat-light-X-ray series; the cyclic type, in the planetary-stellar revolutional systems, and in atomic, molecular, and crystalline organizations. In application to material substances, the revolutional type is predominant in atoms, molecules, crystals, and true solids generally; the vibratory type is most manifest in the true fluidal states; in a special sense it may be said to dominate gases.

THE RELATIVE ENERGY-VALUES OF THE TWO TYPES

In the ultimate analysis of all the cosmic states taken together, the revolutional type greatly preponderates in energy-value. This is not in accord with our sense-impressions. It is a rather singular fact that the values of these contrasted phases of energy are inversely proportional to their *obtrusiveness*. Neither rotations nor revolutions are notably demonstrative, while potential energy of position is only visualized by a mental effort, if visualized at all. The rotation of the earth involves a motion of a fraction of a mile per second; its revolution involves a mean motion of 18 miles per second, while its potential energy of position has a value of 356 miles per second. In this only relations to the sun are included; relations to the rest of the cosmos, in which further great, but only partly known, stores of energy are involved, are neglected.

Over against these great but unobtrusive forms of the earth's energy, stand the very impressive vibratory energies of the heat-light-X-ray series, the specially obtrusive and spectacular energies of the cosmos. While the precise sum total of these cannot be given for lack of adequate data, an excessive estimate may easily be made, and this will serve as a limiting value. According to Lane's law the highest temperature of a condensing body occurs at the stage when it is passing from the gaseous to the liquid state.

Let this stage be assigned the earth in its early history to give it a maximum value of the agitative type of energy. It must then of course have extended far outside its present solid surface. The parabolic velocity—the velocity that carries to infinity—at the present surface, is 6.95 miles per second. It is obvious therefore that the mean velocity of the molecules of the earth-substances could not have been so high as this without dissipating the earth. The maximum mean velocity of the earth-molecules must, therefore, always have been appreciably lower than 7 miles per second. We have, therefore, as the respective mean velocities, something less than 7 miles per second for the vibratory energy, something more than 18 miles per second for the revolutional velocity and—neglecting the rotational velocity altogether—356 miles per second for the potential energy. As the mass is the same in all cases, the energy-values are as the squares of these figures. Reduced and combined, the ratio of the vibratory energy of the earth, on the most generous allowance, cannot be more than 1/2600 of that of the revolutional energy, even when a large factor is neglected. The purpose of this comparison is to show the exaggerated importance that has been given to the agitative phases of energy, as also to the gaseous state, in the study of the earth's energy-values. In this, however, we have only considered the megascopic motions of the earth. We have yet to consider the ultra-microscopic phases in which prodigious energies are even more unobtrusively concealed.

To approach the ratio between the dissipative and the constructive classes of energy in the earth-matter itself, let the familiar case of a bowlder on the surface be taken. Let it have the mean temperature of the earth's surface, say 15° C. Its absolute temperature will then be about 288 centigrade degrees. This represents a linear extension of about .0057. All the rest of its extension represents the work of constructional energy—here interpreted as revolutional energy—except the space occupied by the atomic nuclei and the revolving electrical charges. While the total value of the energy of the revolving constituents of the atoms is undeterminable at present, it is certain that it is almost incomparably greater than that of the 288° C. temperature.

When this atomic energy, which is even more unobtrusive than the energies of celestial revolution, is added to the macroscopic energies, the disparity mounts up to a very high figure. The agitative energies that so deeply impress our senses are really little more than trivial, relatively, in the true cosmic scale.

Now, the resistance that is offered to the compression of an earth made up of solid matter springs mainly from the forces that determine the constitution of this matter. The analysis of these constitutional energies, as now interpreted, involves the electronic revolutions, together with the fields of force and the polarities that spring from them. These may not be all the forces involved—very likely they are not all—but they form the truest picture now available and they may be taken as representative. They are herein made a working-basis, subject to correction as additional light is disclosed.

THE RELATIVE ENERGY-VALUES OF THE POSTULATED EARTH-FORMING NEBULAE

In estimating the potential energy of the nebular matter which, by hypothesis, was condensed to form the earth, in each of the two representative views, the planetesimal and the gaseous or quasi-gaseous, it is assumed, in both cases, that the earth was formed in essentially its present position and relations in the solar system.

In Article XIII of this series,[1] a conservative estimate of the belt occupied by the planetesimals that were later to form the earth, gave it a space-value of 9×10^{23} cubic miles. The gaseous nebula that was to form the earth, measured at the time it first came into self-control and was most extended, had a volume less than 3.5×10^{18} cubic miles. The ratio is about 250,000 to 1. The vastly superior space occupied by the planetesimals, however, does not carry proportional value in potential energy. Its importance chiefly lies in the mode of support of the planetesimals and in their modes and rates of assemblage.

CONTRASTED MODES AND RATES OF ASSEMBLAGE

The modes of concentration were radically different. The planetesimals were sustained in their orbits by velocities of a

[1] *Jour. Geol.*, Vol. XXVIII (1920), p. 678.

mean value of about 18 miles per second. Thus sustained, they only joined the collecting nucleus as variations in their orbits brought them into conjunction with it—a slow process, occupying perhaps two or three billion years.[1] The intervals between the infalls of the planetesimals were, therefore, such that nearly all the heat of their impact with the atmosphere and with the earth's surface was lost before they were buried by added material. The growth of the earth was thus made by the slow accumulation of essentially cold, solid particles mixed at random.

On the other hand, if the earth-forming nebula be assumed to have been gaseous and to have descended along the gaseous line, its volume was sustained by collisions and rebounds of the constituent molecules, and it contracted as fast as the loss of this interaction, i.e., the loss of heat, permitted. Under Lane's law the maximum temperature was reached at the stage when the gaseous body passed into the liquid state. As radiation follows the law of the fourth power, the collapse was relatively rapid; at the most it cannot be assigned more than a few million years.

Enormous losses of energy would be suffered in either the planetesimal or the gaseous mode of assemblage, and so we must take up the question of the earth's primitive energy presently from the opposite point of view: What energy-values were *left* for the evolution after the earth was able to make a record of its own compression? The point of most importance here is the radical difference in the respective factors that controlled the self-compression which followed the nebular concentration. It is obvious that the gaseous descent was controlled by *heat* and that this remained the master factor in the shrinkage of the earth after it became a white-hot molten globe. In the self-compression of the earth built of solid planetesimals, or planetesimal dust, *solidity* was the primary resisting-factor that held the compression in check. The energy-factors in this case were those to which the solidity was due. These are herein interpreted as revolutional phases of energy together with their derivatives. Heat in one case and solidity in the other were then the master factors in the

[1] See "The Rates of Planetesimal Infall," Article XIII, *Jour. Geol.*, Vol. XXVIII (1920), pp. 677 ff.

compression process. In the latter case, the heat generated in the course of the compression was secondary to the revolutional energies. The special courses taken by both the primary and secondary energies become therefore vital elements in the compressional process; to these we shall presently turn.

As indicated above, to form estimates of the energy-values that were inherited by the earth at the stages when it began to make its automatic record of self-compression, it is necessary to enter into a more specific analysis of its status in the two hypothetical cases.

COMPARATIVE VALUES OF ENERGY AVAILABLE FOR DIASTROPHISM

The deformations of the earth are the most available test of the energies that entered into its self-compression, though by no means the only test. There is now no ground to doubt that the diastrophism was large, whatever estimate may be made of its precise value. There must have been enough energy in an available form to actuate the distortions involved, and this energy must have been properly distributed in time and place. The sources of this energy need therefore to be considered in respect to their availability, as well as their adequacy. Fortunately, the problem for all cosmological lines of descent seems to center in the alternative: Was the earth assembled in a fluidal condition dominated by heat, or was it built up gradually by accessions of small fragmental matter in a cool, solid, highly mixed state? If there are tenable hypotheses of an intermediate sort, the considerations that apply to these type-views can easily be adapted to them.

The chief energies available for the evolution from this point on, are (1) the residue of the potential energy of position, except of course what still remains potential; (2) chemical and physical combinations, readjustments, and reorganizations, so far as conditions permitted them to take place during the compression; and (3) the disintegration of radioactive substances, including any other changes in atomic constitution that may have taken place, if any. These atomic factors may possibly have some relation to the extreme stresses that arose from compressional action, but as

there is now no evidence of this, they must be treated under a head of their own.

1. *The period of compression.*—If the earth remained fluidal until all its rock-substance was condensed into a globe, none of the energy lost in the assembling was available for making the observed diastrophic record, since this could only begin after consolidation began. If, on the other hand, the earth was built up of small solid accessions loosely laid down, these must have begun to suffer compression and distortion as soon as one layer was laid on another. The distortional process must in this case have run on thence through the whole history of growth. The compressional and distortional actions were furthermore brought on very gradually and great lapses of time were available to meet the growing stresses by the resources of readjustment, reorganization, metamorphism, and diastrophism.

2. *Availability of the main compression.*—If the earth was assembled in a fluid state, the interior underwent the full measure of fluidal compression from gravitative action before it could make any diastrophic record; little more than the effects of cooling remained available for deformative work after solidification took place. If, on the other hand, the material of the earth was added slowly in a loose, solid state, the main compressive effects entered into the record; for while the distortions in the deep interior would never be accessible, they must have been at all stages the foundation on which the later accessions were built and hence they gave direction to, as well as participated in, the stress effects that arose at every subsequent stage in the increase of mass. They must still continue to participate in the effects of all the more general changes in gravity.

3. *Chemico-physical combinations, readjustments, and reorganizations.*—If the earth remained fluid and convective until fully assembled, almost ideal opportunities for chemical combination and physical adjustment, as well as chemico-physical reorganization, would have been offered, except in so far as the heat itself may have restrained such action. To this extent the chemico-physical resources should have been exhausted before they became available for diastrophism. But if the earth were built up of solid particles

of various sorts mixed by the chance of infall, it would offer almost ideal conditions for recombination, readjustment, and reorganization, which, in this case, would run hand in hand with diastrophism and contribute to it.

4. *Relative exhaustion of potential energy by segregation.*—If the earth was fluid until fully assembled, there should have been facilities for the arrangement of the earth substances in concentric layers according to specific gravity. This would have been a special means of reducing to the lowest terms the potential energy that might otherwise have remained available for deformative work after solidification made a diastrophic record possible. If, on the other hand, the matter remained a heterogeneous mixture so far as intrinsic heaviness was concerned, a corresponding amount of potential energy remained available for the diastrophic record. In so far as segregation by gravity took place during the compression of the mixed solid mass, it co-operated with other deformative processes and left its effects in the record.

5. *Relative exclusion or retention of gaseous constituents.*—If the earth remained fluid and convective until fully assembled, the gaseous constituents should have had favorable opportunities for escape and should have been impelled to escape by the very high heat, so that only such quantities as were required to balance the partial pressures of the same constituents in the atmosphere should have remained to take part in vulcanism later.[1] On the other hand, if the earth was built up by solid particles added slowly to the surface and subjected to weathering and to mixture with air and water, as it was gradually buried, the complex should have afforded almost ideal conditions for the evolution of volcanic gases when it was later subjected to heat and pressure. The phenomena of the moon are especially instructive in this respect, for the gravity of the moon is insufficient to hold free volcanic gases even in its present cold state; much less then in a hypothetical molten state. No equilibrium factor should have been retained in this case. But the evidences of vigorous explosive action on the moon are very pronounced.

[1] Rollin T. Chamberlin, "The Gases in Rocks," *Jour. Geol.*, Vol. XVII (1909), pp. 565–68.

6. *The distribution of the radioactive substances.*—If the earth were assembled in a fluid state, the radioactive substances should have settled toward the center because of their high specific gravity, or else, if convection prevented this, they should have been distributed sub-equally through the whole mass. There should at least have been no concentration of such heavy material in the upper layer. But the special investigators of the subject agree that if the whole earth were as rich in radioactive substances as its accessible portion is, the heat generated would be many times greater than the heat now conducted to the surface and radiated away. Were this true, the earth should have been growing hotter all through its history and no shrinkage at all could be assigned to cooling. On the other hand, if the earth were built up of heterogeneous clastic matter that carried its chance portion of radioactive particles, and if these, by their heating action, liquefied the most susceptible matter immediately enclosing them, and if such liquid matter were then squeezed to or toward the surface by the powerful extrusive agencies that belong to a solid earth, the radioactive substances would be concentrated in the zone of lodgment of these igneous portions. This limits the radioactivity to a degree that seems to fit the observed facts and the theoretical intimations of the case. It is quite obvious that, so far as deformative effects assignable to cooling are concerned, the hypothesis of a molten earth is seriously embarrassed by this newly discovered source of heat superposed on an already embarrassing inheritance of heat from its earlier history, while under the hypothesis of a cold-grown solid earth, it is a welcome agency.

The combined import of all the preceding considerations leaves the fluid earth embarrassingly short, if not fatally short, of resources of energy available for making the observed diastrophic record, while the planetesimal earth is much more amply, and apparently quite adequately, supplied with such energy, and this becomes available in such a slow way as to give great allowances of time for the increments of compressive stress to work out their adjustments and easements along metamorphic and diastrophic lines.

THE INTERCHANGES BETWEEN THE TWO BASAL TYPES OF ENERGY

Before taking up the special modes of the compressional process, the interchanges between the two basal types of energy need consideration. The constructional and the agitative phases of energy are not only interchangeable but interchanges are persistently taking place on the surface and within the earth, and these interchanges play a vital part in the process of the earth's self-compression. The proper recognition of these is indispensable.

Exchanges between thermal and mechanical energy are too familiar to need notice; they are a basal feature in modern industry. But exchanges between agitative and organizing energy, i.e., between vibratory and revolutional energy, as such, though they may not differ in essence from the well-recognized interchanges, need a word of emphasis. Some of these changes from the agitative to the constructive are even more familiar than the mechanical changes, but interpretation has not given them the value to which they are entitled. We know that the grass and the trees grow, but we easily overlook the fact that such growth is a widespread and important endothermal process. It belongs to the unobtrusive class and does not enforce attention. The prairie fire and the holocaust of the forest, the complementary exothermal process, command our lively attention. The unobtrusiveness of endothermal action is likely to deceive us as to the balance between interchanges of energy in nature. The problem in any special case is to determine the balance between opposing actions. There is, however, no doubt as to a real preponderance of exothermic action on the earth's surface. When lavas come up from below, they usually undergo exothermic reactions to a greater extent than endothermic reactions. This in itself raises the question whether endothermic reactions are not preponderant in the region whence the lavas come. Van Hise,[1] Leith,[2] and their associates, have shown by the extensive collection and study of data from the full

[1] C. R. Van Hise, "A Treatise on Metamorphism," Monogr. XLVII, *U.S. Geol. Surv.* (1904).

[2] C. K. Leith and W. J. Mead, *Metamorphic Geology*, Henry Holt and Co. (1915). See particularly the chapters on "Katamorphism" and "Anamorphism" in both works.

range of the accessible terranes, that while exothermic reactions preponderate in the outer or katamorphic zone, the preponderance is reversed below and endothermic reactions take precedence in the anamorphic zone. It is to be noted that while katamorphic action, exothermic action, and the lowering of density, commonly go together, as also anamorphic action, endothermic action, and rise of density, they do not invariably coincide; and further, that none of these necessarily excludes the others from any horizon. The essential question is not one of exclusive action but of preponderant action.[1] It is in the natural order of things that in the great contact zones between the atmosphere, the hydrosphere, and the lithosphere, there should be a trend of energy toward its agitative phases, and that in the stabler solid zones below there should be a compensating trend toward the constructional and the persistent, without limiting either zone to one type of action. In terms of the two basal types of energy, exothermic action, on the average, involves a change of organizing or revolutional energy into vibratory-dissipative energy; while endothermic action is commonly the reverse.

THE CONDITIONS THAT DETERMINE THE INTERCHANGES

In a very broad sense, open conditions and freedom from pressure or other forms of restraint, favor exothermal reactions, while confinement and pressure favor endothermal reactions. Any form of crowding, even self-stress, naturally tends toward *divergence* of energy into the various paths available to it, since this affords relief. The higher the stress, the more it forces itself into unoccupied paths. Concentrative stress, therefore, favors the passage of a portion of the energy along endothermic lines and the formation of dense substances; while dispersive stress, low stress, and no stress, are less compulsory and give exothermic action freer scope. Apparently crowding is not confined to imposed stresses, but arises from what may be styled the self-stress of the activity. A small mass of gas in open space exerts little interior stress upon

[1] Compare C. K. Leith, "The Structural Failure of the Lithosphere," Vice-Presidential Address, Geol. Soc. Amer., *Science*, N.S., Vol. LIII (March 6, 1921), pp. 205–7.

itself, and only the larger vibrations are in evidence, but if the mass grows indefinitely the internal self-stresses increase and there appear in succession the shorter and more intense vibrations ranging up through the whole gamut of vibrations to the X-rays and doubtless beyond. There is, in this, increased pressure, of course, but the activity itself is increasingly *divergent* as well as increased in amount. However this may be interpreted, there is a growing complexity of vibration, and it seems to be a safe generalization that growing mass and growing internal pressure are attended by increase in the diversity of phases assumed by the compressional energy; in other words, there are more varied partitionings of the energy and it takes a larger number of paths, including more frequent interchanges between the endothermic and exothermic phases. As there is thus crowding in various directions for easement, the direction that gives greatest relief from the stress imposed by the environment naturally becomes a predominant trend. Where there is high pressure and it is unescapable, the line of relief is the passage of energy into a constructional form that gives additional density. Where the pressure is weak or absent, an expansional or dispersive form of energy may be more efficient in giving relief. Both forms are likely to be present and to co-operate with one another in any pronounced case.

THE TESTIMONY OF PRESENT INTERNAL STATES AS TO THE DOMINANT DIRECTIONS TAKEN BY ENERGY IN THE INTERIOR

Tidal[1] and nutational[2] evidences concur in indicating a higher degree of rigidity and elasticity in the interior, taken as a whole, than in the outer shell. Seismic waves add very specific confirmatory evidence, so far as the outer seven-eighths of the volume of the earth is concerned. The seismic evidence for the remaining central part is as yet obscure, and is differently interpreted by the special students of the subject. In a general way, the whole of the interior is covered by the tidal and nutational evidences. These favor the interpretation of the central part as highly rigid and elastic, since

[1] A. A. Michelson and Henry G. Gale, "The Rigidity of the Earth," *Jour. Geol.*, Vol. XXVII (1919), pp. 585–601.

[2] W. Schweydar, "Die Elasticität der Erde," *Naturwissenschaften*, Part 38. Potsdam, Germany (1917).

these qualities fit the general import of the evidence, but for the present it is prudent to leave the question of the state of the center to be settled in the future. It is to be observed that the increasing density of the interior tends to dampen the speed of the seismic waves, and that correction for this effect must be made in deducing the inward increase of rigidity and elasticity from the seismic records. When allowance is made for this, the generalization that rigidity and elasticity are notably higher in the interior than in the outer shell is put beyond serious question. This means that in the partition of the compressional energy between those phases that increase the rigid elastic attachments of the molecules to one another and those phases that weaken or destroy these attachments, the former have been favored in a marked degree. This is testimony of a most cogent sort. By interpretation, this signifies that only a minor part of the compressional energy took the vibratory form in the interior, the major part taking the revolutional or constructive form, and that in doing this it served to promote compactness and the strength of hold of the constituents on one another.

DID THE ORGANIZING ENERGY EFFECT CHANGES IN THE CONSTITUTION OF THE ATOMS?

Lest the seeming needs of the case bias us toward one conclusion rather than another, let us hasten to note that the mean density of the earth, compared with the probable density of the original matter, is such as to offer no real ground for bias in favor of atomic construction, for the higher density of the interior is fully accounted for by the density gradients that arise from metamorphism in the zone of observation. Atomic construction, if invoked as an aid, might as easily render the interior mass too dense, as to help explain the density as it is. Nor is there more than uncertain evidence bearing on the atomic question; but the matter is too important to be ignored in a discussion of the effects of compressional energy.

The most remarkable of known exothermal effects connected with rock-substance springs from the spontaneous atomic disintegration of the heaviest known elements. No evidence that this

disintegration has anything to do with relief of pressure, such as might be assigned to their rise from the interior, is now available. Any such possibility must be left to the revelations of the future. It is logically necessary, however, for one who believes in the indefinite cyclic persistence of the cosmos, to suppose that the present exothermic action is the reversal of an endothermic process that gave these elements the stores of energy they are now so persistently and systematically discharging. The place and time and conditions of this storing action are altogether open questions. By interpretation, the energy now being given out springs from intense revolutional action, for revolutional motion seems to be the only probable way in which such prodigious energies can be stored in so unobtrusive a state and given out so regularly and systematically and in such concentrated forms. The storing process must probably have involved somewhat similar forms and intensities of action. One of the most common speculations as to the place and conditions of this storage process, locates it in some center of great stress where pressure and heat co-operated. This should perhaps be amended by recognizing that the more intense vibratory agencies of the X-ray end of the series were even more probable agencies, because their motions were more nearly commensurate with the minute and swift revolutions that are supposed to store the energy in question. The center of the earth is possibly a place of the right type, but it belongs to an inferior order compared with the centers of stars, unless solidity counts for something. In this case the center of the earth might have a preferred place, since our planet is among the largest of known solid bodies. An alternative speculation places the origin of the radioactive substances in the outlying regions of space.

There is perhaps a suggestion of general atomic change in the remarkable phenomena of thermionic emission, contact potentials, and photoelectric action. These seem to imply that there is some kind of commensurability between the extremely intense oscillations of the vibratory activities and the orbital periods of the electrons, so that effective interaction and perhaps interchange takes place between them. Commensurability is perhaps the property by which interchange is effected between the minutely

vibratory and the minutely revolutional phases of energy. These speculative suggestions have little value beyond helping to make it clear that it is by no means safe to assume that atomic construction and destruction are not common functions of the interior.

WHAT AMOUNT OF COMPRESSION IS IMPLIED BY THE MEAN DENSITY OF THE EARTH?

As already noted, there is no need to push appeal to the organizing functions of energy in the interior so far as to assume the building up of atoms for the sake of explaining the higher density of the earth's interior; indeed, if there is any constructive work of that sort, the increase above the decrease of density cannot go very far without making the mean density too great to fit the evidence. If we assume that the primitive matter had the meteoric density of 3.69 adopted by Farrington, and compare this with 5.53, the mean density of the earth adopted by Moulton, the mean increase in density due to compacting, reorganization, atomic change, etc., is only about 50 per cent. Or if, to assume an improbably low figure for the density of the earth's original matter, we take the moon's mean density, 3.34—assuming that the effects of compression at the moon's center are offset by the porosity of its outer part—the increase in the earth's mean density would be only a little over 65 per cent. In either case, or on any plausible assumption, some part of the compacting must be assigned to mechanical compression, so that the increase of density assignable to reorganization under the special conditions of the interior is not very large.

THE INTIMATIONS OF THE DENSITY GRADIENT IN THE ZONE OF OBSERVATION

Geologists have been at great labor to compile thermal data from mines and deep borings that they might deduce from these a temperature gradient that would throw light on interior conditions, but the same line of attack on the rising density of the interior seems to have been overlooked. It is to be recognized, of course, that neither of these gradients can be projected to the center of the earth without reservation, for both curves probably fall off notably in the interior, but the density curve is probably as trustworthy a

guide as the temperature curve, for, in the planetesimal earth, both arise from compression and its direct and indirect consequences.

After an elaborate study of the most reliable data, Dr. H. S. Washington thus sums up his conclusions in a recent paper:[1] "I am inclined to place the average density of the crust at about 2.75 at least for the uppermost shell, while that of 2.80 would probably be nearer the truth for an average of any considerable depth, say 20 miles or more." The mean depths of these two shells can scarcely be more than 8 or 10 miles apart. The rise of density in this little difference of depth, if projected to the earth's center, would give a density there nearly twice that computed from the classic law of Laplace, or from the law of Roche specially formulated to meet the astronomical requirements. No account is here taken of mechanical compression, for the specific gravities adopted as the basis of the estimates were all taken under atmospheric pressure. Much less was any account taken of hypothetical quantities of metals or other specially heavy material, for both these shells are formed of common rock.

The two elements most common in the zone of observation, oxygen and silicon, often unite to form tridimite in the outermost shell but not in the plutonic rocks, where the same elements appear as quartz. This distribution is commonly assigned to differences in the physical conditions of the two horizons, especially differences in pressure. The specific gravity of tridimite ranges from 2.28 to 2.33, while that of quartz is 2.65. There is thus a rise of density of 15 per cent, so far as these minerals are concerned, between two horizons both of which lie in the limited zone made accessible by deformation and denudation.

The most instructive and suggestive data, however, are found in the progressive stages of increase in density developed in several different kinds of silts as they pass into various kinds of schists, and thence, in part, into a group of heavy minerals of which the garnets may be taken as types. The compression of the silts into shale may be neglected since a notable part of the increased density

[1] H. S. Washington, "The Chemistry of the Earth's Crust," *Jour. Franklin Inst.*, December, 1920, p. 804.

of the shale was due to the mechanical elimination of porosity. In forming the schists there was true reorganization with increased density, and still later there was further partial reorganization into much heavier minerals of the garnetic group. In the case of the garnets there is a rise in density from the schist minerals which formed them of 36 to 84 per cent, as pointed out by Van Hise.[1] In these cases the rise of density is unequivocally the result of the metamorphic reorganization of very common and representative kinds of material. It is to be noted further that one reorganization follows another even in this limited zone.

These specific cases show the possibilities and the actual tendencies to increase of density by metamorphism, quite apart from mechanical compacting. They point to the very significant fact that the chief density effects are to be sought in metamorphism rather than mere mechanical compacting by pressure. The crux of the compressional problem therefore lies in metamorphic reorganization, in selective liquefaction, and in the extrusion of magmas. The concrete task thus imposed is the tracing of the paths followed by the compressional energy and the study of the kind of work each phase of energy does. The specific phenomena to be explained are (1) the rising density, rigidity, and elasticity of the interior material; (2) such a distribution of density as to satisfy the intimations of the precession of the equinoxes and the nutation of the poles; (3) the amounts and kinds of diastrophism recorded in the structure of the earth; and (4) the protrusion and persistent maintenance of the continents and the complementary depression of the ocean basins, as well as the special configurations of the earth. It is not sufficient to explain these separately by isolated postulates. unless these are shown to be mutually compatible and connected with a common origin; these features are to be explained as a co-ordinate group of phenomena arising from a common origin and a common line of dynamic procedure.

THE SPECIFIC PATHS OF THE COMPRESSIONAL ENERGY

In the following analysis, it is to be understood that the earth is assumed to be, and to have been at all stages after the formation

[1] C. R. Van Hise, *op. cit.*, pp. 205 ff.

of its collective nucleus, a solid body, built of heterogeneous planetesimal matter at the start, that it was subjected to a slowly growing gravitative pressure whose total accession was spread over a period of the order of two or three billion years, and that there were large allowances of time for metamorphism and for the adjustment of the strain arising from each increment of pressure. On these assumptions the chief partitions and paths of the compressional energy, seem logically to have been as follows:

The first step was the partition of the initial increment of energy by the passage of a part of the stress into strain, while another part took the thermal form. So long as the strain lasted, its energy was stored or latent. A varying but large measure of energy seems thus to have been stored all through the geologic ages. It appears from stratigraphic evidence that the strain-limit in the sub-surficial material has been high enough at several periods to permit the accumulation of stored energy sufficient to actuate declared deformative "revolutions" in spite of such partial easement as may have taken place, during the stages of accumulation, from the milder forms of idiomolecular action about to be described.

The second step in the compressive process was the co-operative action of the stored energy of strain and the agitative thermal energy. The latter aided change by loosening the fixed elastico-rigid attachments of the molecules, the essential properties that gave rigid symmetry to the crystals and solidity to the amorphous fragments. The hold of crystals and of clastic fragments upon their constituent molecules was unequal because some of them lay at the angles, or on the edges, or on sharp curves of the little masses, where fewer other molecules supported them. So also the strains arising from pressure upon the interlocking crystals or fragments was greatest on these outlying molecules. The particular molecules thus least securely held and those most severely strained, yielded first. This eased the strain on these particular points and threw the stress on new molecules; from this, new action of like order arose and the process was essentially repeated.[1]

[1] In many cases, especially near the surface, solution and chemical reaction greatly aided molecular transfer and crystalline reorganization, but these are accessory agencies rather than factors of the compressional process, as such.

The detached molecules of this first action, responding to such stress as was then felt by them in their relatively free state, took the lines of least resistance until they reached some point where the organizing force of some crystal, so situated as to be able to grow, brought them under control and reattached them with due orientation. Such reattachments were obviously conditioned by the balance of strength between the crystalline force and the weakest phase of the general pressure. As a result the growing crystal extended itself most in the line of least resistance and co-operated with other crystals of like situation in developing parallelism of structure.

It is obvious that such individual actions on the part of single molecules acting by themselves, and acted upon by special stresses, could take place while as yet the *general* strain was far below the strain limit and *general* detachment could not take place. If the pressure came on slowly enough, the whole crystal or fragment might be broken down in this piecemeal way while the general strain was below the mean strain-limit. As only a few molecules were in transit at any given time, the mass as a whole would remain solid throughout the process.

The action was thus the special work of individual molecules, each suffering its own strain and playing its own part in its own way, i.e., it was *idiomolecular*. The process is sharply distinguishable from the common movement of all molecules, such as usually takes place when liquids flow. The process may be studied to advantage in the granulation of snow at temperatures that inhibit liquefaction.[1]

So long as the stress and strain were mild, the foregoing action was obviously slow and had rather narrow limitations. But with notable increase of stress, giving rise to increase of strain, and increase of heat, the process appears to have been hastened and given a tendency to collective action in parallel lines, planes, or belts, doubtless because resistance was less effective against such

[1] C. S. Peet and E. C. Perisho, working with the writer in the winter of 1894, found by daily micrometric measurements of many granules, that the larger ones grew every day whether the temperature was at, above, or below 0° C., the growth apparently taking place at the expense of the smaller, more sharply curved granules.

united action. This apparently went so far in some cases as to verge toward general simultaneous molecular action, but analysis seems to show that it remained idiomolecular in actual method. From such quasi-collective but really idiomolecular action, cleavage, schistosity, and other forms of structural parallelism arose. In glaciers this idiomolecular type of action seems to range from snow granulation to the point where fracture takes place and the movement becomes a massive shear.[1]

By further increases of pressure, the strain limit *along selected lines* was reached and definite fracture and shear took place, or else the whole mass was crushed to fragments. In either of these cases, the action became diastrophic rather than metamorphic.

It has been very generally held that when such depths and pressures are reached as to inhibit fracture, general movement of the molecules over one another after the manner of liquids must take place. The original idea of "rock flow" seems to have sprung from this notion. In a highly rigid body, such a general movement of molecules upon one another requires the breakage of all the bonds between molecule and molecule and so *involves a maximum of force*. Moreover, this force must come from *differential* stress, since *balanced* stress, within limits, forces the molecules into closer and stronger relations. The supposed "flow" seems improbable except when true liquidity, which destroys the special rigid bonds of the solid state, is brought about. So far as differential stresses affect the solid matter of the interior, easement by idiomorphic action, either collective or isolated, seems to require much less energy and is hence more probable. With the open structure now assigned matter, and with the abundant evidence that molecules really collect into crystals in the midst of rock that seems quite solid, and with other phenomena giving evidence that in some way molecules creep through solid matter, there seems no substantial ground for excluding idiomolecular action from the deep interior.

[1] It was from the study of the granulation of snow, the growth of glacial granules, and the development of schistosity in the glaciers of Greenland, in 1894, that the method and importance of this individual action of molecules, while the mass remained solid, was first realized by the writer. "Glacial Studies in Greenland," Presidential Address, *Geol. Soc. Amer.*, Vol. VI (1895), pp. 209–14.

In tenacious solids where impact takes place at high velocities and with prodigious force, as in the case of a steel target struck by a solid shell, there is no time for idiomolecular action, and very little for any form of selective or metamorphic action, and so all molecules are apparently caused to move over one another in a way that is scarcely distinguishable, if at all, from real flow. The slowness of the increases of stress in the interior of the earth, however, is thought to put deep-seated diastrophism in a quite different category from this velocity-stress action.

Although fluidal action is placed in a secondary order in the evolution of a planetesimal earth, the formation and extrusion of magmas play a very important function in its compression, but that must be left for a later article.

FIELD OBSERVATIONS IN NORTHERN NORWAY BEARING ON MAGMATIC DIFFERENTIATION

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Recent years have witnessed a marked development in the understanding of differentiation processes. Petrographers have tried to get away from the purely theoretical considerations about the matter and to harmonize the conclusions from the field observations with the results of synthetical experiments on silicate minerals and their crystallization obtained by the Geophysical Institute at Washington and others. Although these experiments are still far from covering all subjects involved, and although the multitude of field observations from most parts of the earth are often contradictory, there seem to be certain lines of development which prove promising.

The results now generally converge toward the conclusion that an ordinary fluid silicate magma, without concentrated mineralizers, is not capable of splitting up into two magmas mutually insoluble or with limited solubility. Accordingly, the main part of the differentiation processes is transferred to the period of crystallization, resulting in considerable restriction of possibilities.

According to this supposition, naturally the first mode of separation to be considered was that of the heavier crystals from the lighter ones and from the still fluid magma by gravitative settlement. In a number of instances this sort of differentiation has definitely been proved to occur. But it also became obvious that this sort of separation could not alone account for a great many differentiation processes actually observed.

The newer theory of squeezing differentiation—quite as well in accord with the latest results—seems to be capable of a more general application in those very frequent instances where lateral

[1] State mining geologist, Geological Survey of Norway.

pressure prevailed during crystallization. This theory was suggested by A. Harker, and especially after it had been formulated and developed by N. L. Bowen[1] it has aroused keen interest among petrographers. In the present paper I have attempted to give some examples from northern Norway bearing on this sort of differentiation.

SHORT REVIEW OF THE GENERAL GEOLOGY OF CALEDONIAN

As known, the Caledonian mountain chain—of late Silurian to early Devonian age—traverses the whole length of Norway from SSW. to NNE., in its northern part occupying nearly the whole breadth of the country. The axis of the chain forms a marked geosynclinal depression of the old Archaean Scandinavian shield and of the pre-Cambrian peneplain. The depression is filled with a very thick series of sediments, strongly folded and metamorphosed.

It is supposed that the whole of Scandinavia has been covered by the Cambro-Silurian sediments, remnants of which are found at many places above the Archaean rocks. They are unmetamorphosed and unfolded wherever well beyond the Caledonian folding region. Toward this old mountain chain, first folding sets in, then we meet an increasing degree of metamorphism, which attains its maximum at the axis of the chain. In the same direction the thickness of this series of sediments increases markedly. In the eastern, unfolded zone (especially in Sweden) the total thickness is generally only some few hundred meters, in the folded but unmetamorphosed Kristiania region the thickness surpasses 1,000 m., and toward the mountain chain it reaches several thousand meters.

Although no determined fossils have yet been found in the metamorphosed sediments of *northern Norway*, there are several reasons to believe that the sediments here represent the same Cambro-Silurian series. The original sediments in the geosyncline were extensive layers of slates, marls, limestones, and dolomites, with subordinate sandstones. The metamorphism has been

[1] N. L. Bowen, "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, Vol. XXIII (1915), suppl.; "Crystallization-Differentiation in Igneous Magmas," *ibid.*, Vol. XXVII (1919), pp. 393 ff.

very strong throughout the region, producing garnet-mica schists, marbles, quartzites, etc., but generally not with the development of lime-silicate minerals.

In this region there has not been disclosed any unconformity or discontinuity in the sedimentation.

During the Caledonian folding this series was intruded by great masses of eruptive rocks, especially in the axial part of the chain. Most of these are ordinary granites.

There also occur in considerable quantities femic eruptives, very intimately intruded in the schists, and like these thoroughly metamorphosed to amphibolites and different eruptive gneisses. They are much differentiated, the last products generally being soda-rich granites (or Trondhjemites).

Moreover, we find as isolated fields more extensive areas of gabbroidic eruptives, less metamorphosed, sometimes nearly fresh. They were also intruded during the Caledonian folding period and are chemically nearly associated with the former group, from which they do not differ very much, if at all, in age. They also show marked differentiation and on account of their relative freshness afford very interesting petrographical material.

All the eruptives seem to belong to the same cycle of orogenic intrusions. Original lavas or tuffs, which occur in great masses in the Trondhjem district farther south, have not yet been identified among them.

The intrusions have everywhere occurred under a heavy load of sediments, and the whole complex must have been heated to a considerable temperature.

Outside the real root of the mountain chain all eruptives seem to have been intruded completely parallel to the schists. Especially in the district to be considered here, we nowhere find crossing eruptive dikes or other eruptive bodies cutting the schistosity (excepting the pegmatite dikes). It seems to have been a general rule that the magmas, after intrusion, were subject to *magmatic migration* between heated schists, from the root of the mountain chain outward. In this way the magmas may have wandered for very considerable distances from the places where they broke into the schists, until they came to rest. The moving force was induced

by the orogenic folding itself, and lateral pressure existed throughout the crystallization period.

THE RAANA NORITE FIELD (FIGS. 1 AND 2)

This eruptive body, to be especially considered here, is situated at the south side of the Ofoten Fjord, west of the known harbor of Narvik, at 68°20′ latitude. It has recently been closely investigated by the author on account of discoveries in the last years of extensive but poor deposits of nickeliferous pyrrhotite.

In the very rugged country with steep mountains rising directly from the sea and differences in height of more than 4,000 feet, the whole eruptive mass is exceedingly well exposed, and the results of differentiation can be followed in all details.

The norite is injected into a thick series of garnet-mica schists with some interstratified layers of marble. The injection is parallel to the schistosity and forms a lens-shaped body with a thickness of about 3,500 m. and a diameter of about 12 km. The relative thickness of the lens is greater than is generally the case in this sort of intrusions, and is supposed to be due to the influence of some E.–W. folding axes. The section of the eruptive body with the present surface has an area of 67 km.^{2}, 3 km.^{2} of which has been cut off by erosion. No offsets or crossing dikes occur in the surrounding schists.

The very first investigation teaches that the norite field is not homogeneous throughout, but is composed of a central mass of *quartz-norite* and a very considerable and continuous marginal zone of more femic *normal norite*, occupying the border against the schist all around the field to a width of one-third to one-fourth of the whole diameter.

To understand the reason for this, it is important to know the tectonic position of the eruptive mass. One might of course be tempted to believe that the field after differentiation might have been thrown down in an inverted fold, and that the basic border zone accordingly should represent the lower part of the magma basin, separated out by gravitative differentiation in the same way as is the case in the Sudbury field. This, however, is definitely

proved not to be the case. The norite body forms a lens in its normal position between the schists, with a mean dip of about 30°, and the basic border zone is quite as well developed in the upper as in the lower part of the lens.

Between the quartz-norite and the normal norite there is no eruptive contact, but a gradual though rapid transition.

As a third group we may unite all the olivine-bearing rocks: *lherzolites*, *troctolites*, and *olivine-norites*, generally very rich in olivine and sometimes nearly of dunitic composition. They occur as very numerous, greater or smaller bosses and bands in the normal olivine-free norite of the marginal zone, but never in the central quartz-norite.

In the marginal zone they occur irregularly distributed all through it from the outer contact with the schists toward the inner border against the quartz-norite and all around it, quite as numerous in the upper as in the lower part of the eruptive. They strike one as being swimming bodies in the norite magma. It is easily proved that they are neither younger intrusions nor older inclusions, but are very nearly of the same age as the environing norite.

While the above-named groups of rocks are all very nearly related and form a stepwise but nearly continuous series without definite eruptive contacts, there is chemically and tectonically a gap between these and a last group of eruptive rocks. The latter form well-defined dikes, cutting all the former rocks and consisting of an aplitic *soda-rich granite*. That they belong to the same eruptive series, with their source in the central part of the lens, is proved by the fact that they are confined to the norite field and occur in greatest quantity in the central field of quartz-norite. Here they form a network of narrow dikes, occupying about 7 per cent of the total area. The dikes are well defined, but with slightly blurred contacts. The same dikes occur also in the marginal norite, here only occupying about 3 per cent of the area, but more regularly and with razor-sharp contacts.

The very last products of volcanic action are some irregular veins of pegmatitic *potash-granite* and of snow-white, pure *quartz*, both carrying black tourmaline.

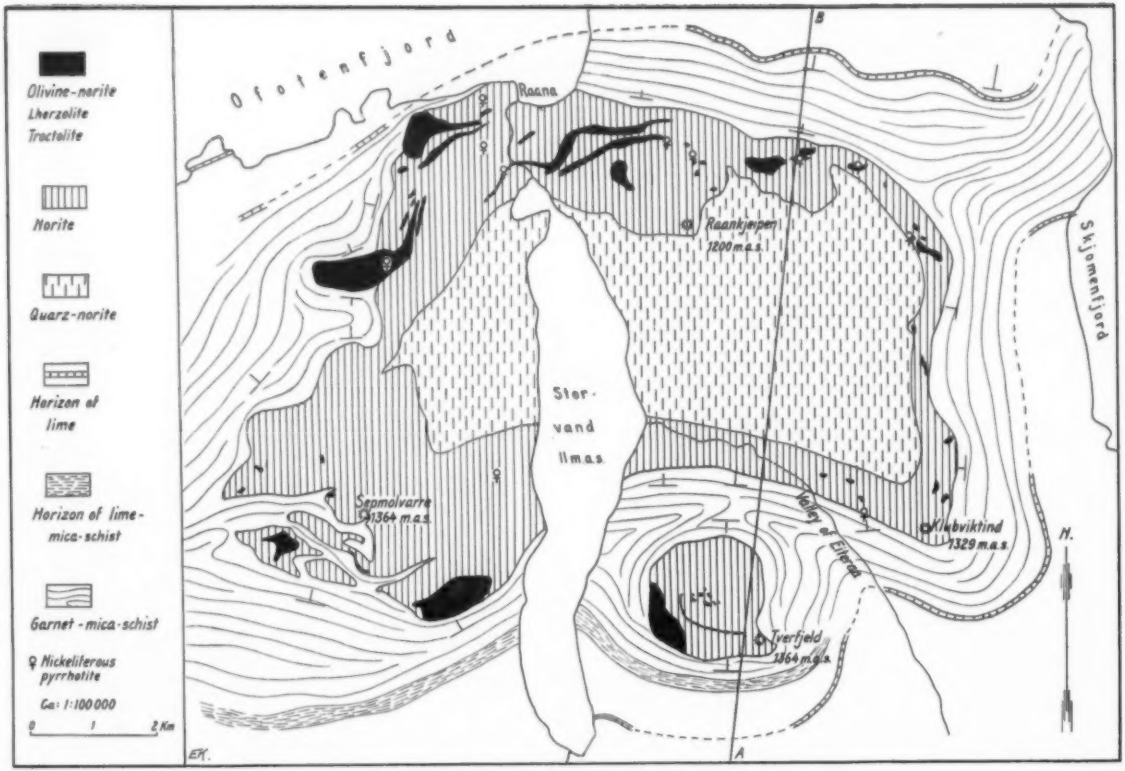

FIG. 1.—Map of the Raana norite field. Scale, 1:100,000

The distinct gap between the main mass of massive norites and the dike-formed acid differentiation products of aplitic granite reminds us very much of corresponding features of the "red rock" in the Duluth gabbro.[1]

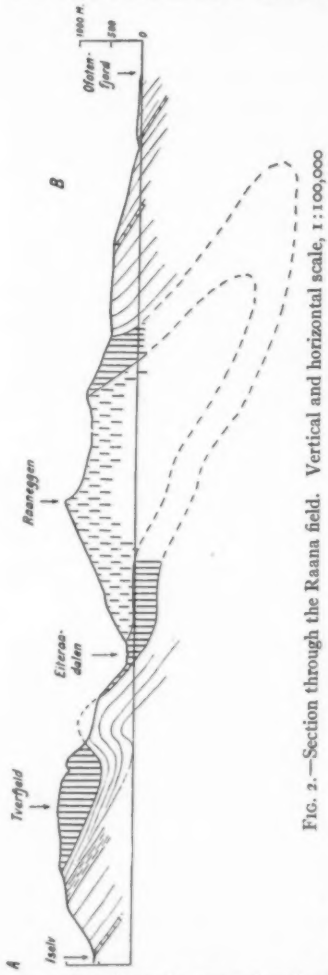

FIG. 2.—Section through the Raana field. Vertical and horizontal scale, 1:100,000

The deposits of nickeliferous pyrrhotite—which will not be treated here—are in their occurrence confined to the olivine-bearing rocks and to the marginal normal norite, and no traces of them are found in the quartz-norite or the younger dikes. In the olivine rocks the sulphides occur only as impregnations, but are relatively very rich in nickel. While the percentage of sulphur generally is between 1 and 2 per cent, the nickel content nevertheless reaches 0.7 per cent, of which not more than 0.1 per cent seems to be in the form of silicate in the olivine mineral. In the norite, the sulphides occur partly as impregnations, partly as segregated richer masses, but the nickel content in the pure sulphide is lower, generally between 1.5 and 4 per cent.

The mineralogical composition of the rocks is as follows:

The *olivine-bearing rocks* consist of olivine, rhombic and monoclinic pyroxene, and plagioclase, but generally no primary biotite. Accessory constituents are picotite, green spinel, magnetite, and pyrrhotite. The rhombic pyroxene is an enstatite with less than

[1] Frank F. Grout, "A Type of Igneous Differentiation," *Jour. Geol.*, Vol. XXVI, pp. 626 ff.

17 per cent ferrous silicate, the monoclinic pyroxene is a diallage. The plagioclase is always bytownite, about $Ab_{20}An_{80}$, nearly without zones, and occurring interstitially between the other minerals.

In the *normal norite* the minerals are: Hypersthene with abous 25 per cent ferrous silicate, poikilitic diallage in big individualt with hypersthene inclusions, labradorite-bytownite, often with zonal structure and varying composition, from 50 to 80 per cent An, and some primary biotite. Uralitization occurs in many parts of the field, but has no interest in this connection. The considerable variations in this rock seem exclusively to be due to quantitative variations in the relative proportion of pyroxene and plagioclase. The monomineralic rocks, anorthosite or pyroxenite, are however, never developed.

The *quartz-norite* contains iron-rich hypersthene with 40–45 per cent ferrous silicate, much diallage, which is here not poikilitic, but crystallized at the same time as the hypersthene, and further generally plenty of biotite. The plagioclase is labradorite with marked zonal structure, from 40 to 55 per cent An. Besides, this rock always contains small amounts of microcryptoperthitic orthoclase, rich in natron, and of free quartz.

The *aplitic granite* dikes contain quartz, oligoclase with 26 per cent An, non-perthitic microcline, and a little muscovite and biotite.

The *pegmatitic granite* dikes contain quartz, perthitic microcline with a faint green color, and black tourmaline. The perthite consists of 87 per cent microcline and 13 per cent albite-oligoclase with the composition $Ab_{83}An_{17}$.

The chemical composition of the differentiation products is seen from the analyses in the following table, where the calculated norm is also given.

The mode of these rocks naturally differs somewhat from the norm, even apart from secondary processes. So the potash, instead of forming orthoclase, partly enters into plagioclase and biotite, while part of the lime together with aluminia enters pyroxenes instead of plagioclase.

After an exact microscopic measurement, I give the mineral composition actually found in the normal norite and the quartz-norite, corresponding to the analyses No. 3 and No. 6 respectively.

ANALYSES

	(0)	1	2	3	4	(4a)	5	6	7
SiO_2	52.6	41.74	41.32	52.30	50.10	50.10	50.70	55.90	72.20
TiO_2	0.4	0.12	0.08	0.62		0.5	0.25	0.45	0.39
Al_2O_3	16.2	2.87	7.71	10.28		18.5	20.70	17.50	14.22
Fe_2O_3	0.5	2.96	1.83	0.37	26.75	0.5	0.50	0.08	0.55
FeO	6.7	10.66	8.63	8.80		6.3	4.38	6.07	2.00
MnO	0.1	0.35	0.13	0.20		0.10	0.07	0.09	0.03
MgO	12.2	38.70	35.26	18.30	12.54	12.54	9.43	5.98	1.03
CaO	7.7	1.48	2.22	6.06	8.65	8.65	10.35	8.32	2.60
BaO	Trace	.....	None	Trace	.....	.....	Trace	Trace	0.02
Na_2O	1.8	0.63	0.54	1.14	.....	1.5	1.58	2.75	2.55
K_2O	1.0	0.24	0.98	0.58	.....	0.6	0.69	1.50	3.78
P_2O_5	0.05	0.09	0.06	0.05	.....	0.05	Trace	0.05	0.08
V_2O_3	0.06?	.....	.....	.....	0.09	0.09	.....	.....	.....
S	0.06+	0.12	0.28	0.09	.....	0.05	0.05	0.05	Trace
Ni	.....	0.14	0.36	.....	.....	.....	.....	.....	.....
Cr_2O_3	0.06	0.05	0.10	.....	0.09	0.09	0.08	None	.....
Cl	.....	.....	.....	.....	.....	.....	.....	.....	Trace
F	.....	.....	.....	.....	.....	.....	.....	.....	Trace
CO_2	.....	None	None	0.61	.....	.....	0.40	0.20	0.06
H_2O+	0.7+	0.25	0.39	0.86	.....	0.7	1.12	0.50	0.65
H_2O-	.....	(0.03)	(0.04)	0.06	.....	.....	0.07	0.07	0.06
Total	100.13	100.40	99.89	100.32	.....	.....	100.37	100.41	100.22
+O for S	.....	0.06	0.14	0.05	.....	.....	0.03	0.03	0
Total	.....	100.34	99.75	100.27	.....	.....	100.34	100.38	100.22

CALCULATION OF THE NORM

	(0)	1	2	3	4	(4a)	5	6	7
Quartz	.....	.....	.....	.....	.....	.....	0.66	4.48	34.74
Orthoclase	6.12	1.39	6.12	3.34	.....	3.34	3.89	8.88	22.24
Albite	15.20	5.34	3.99	9.43	.....	12.58	13.62	23.23	21.48
Anorthite	33.08	4.31	11.12	21.41	.....	41.98	47.26	30.88	12.79
Nefeline	.....	.....	0.39	.....	.....	.....	.....	.....	.....
Corundum	.....	.....	1.53	.....	.....	.....	.....	.....	1.22
Σ sal	54.40	10.04	23.15	34.18	.....	57.90	65.43	67.47	92.47
Diopside	2.44	1.65	.....	3.56	.....	0.89	1.33	7.20	.....
Hypersthene	39.82	5.92	.....	56.26	.....	31.95	30.20	23.45	5.84
Olivine	0.62	76.52	72.72	1.98	.....	6.88	.....	.....	.....
Magnetite	0.70	4.41	2.55	0.46	.....	0.70	0.70	0.12	0.70
Ilmenite	0.76	0.22	0.15	1.22	.....	0.91	0.46	0.85	0.76
Apatite	.....	0.34	.....	0.12	.....	.....	.....	0.12	.....
Chromite	.....	.....	0.15	.....	.....	0.15	0.10	.....	.....
Pyrite	.....	0.22	0.53	0.17	.....	0.10	0.10	0.10	.....
Σ fem	44.34	89.28	76.10	63.77	.....	41.58	32.92	31.83	7.30
MgO:FeO[mol]	3.5:1	7.3:1	7.3:1	4:1	.....	.....	4.3:1	1.6:1	1:1

KEY TO THE TABLE OF ANALYSES

No.	Petrographic Name	Symbol	Locality	Analyst
(0)	Calculated composition of undifferentiated magma	III.5.4.4	.....	.....
1	*Lherzolite*	(IV) V.1."5.1.(1) 2	Raanbog River	Naima Sahlbom
2	*Troctolite*	IV.1.5.1.1 (2)	Tverfjeldet	Naima Sahlbom
3	*Normal norite*	(III) IV.1.1.1.2	Source of Raanbog River	Olaf Röer
4	*Normal norite*	Partial analysis	Source of Raanbog River	Naima Sahlbom
(4a)	Calculated after 4	"III.5.4".4	.....	.....
5	*Uralitized norite*	II".5.4".4	Arneskaret	Olaf Röer
6	*Quarts-norite*	II"."5.(3) 4.4	Stemnes in Raana	Olaf Röer
7	*Aplitic granite*	I".3 (4).2 (3).3	Sepmolvarre	Olaf Röer

While the composition of the quartz-norite is pretty uniform throughout, the marginal norite varies considerably. The analysis No. 3 represents a type very rich in hypersthene, analysis No. 5 a type rich in plagioclase, and analysis No. 4 a mean type.

	Normal Norite, No. 3 Weight Percentage	Quartz-Norite, No. 6 Weight Percentage
Quartz	None	2.1
Orthoclase	None	4.7
Plagioclase	20.0 (*ca.* $Ab_{40}An_{60}$)	59.2 ($Ab_{33}An_{67}$)
Diallage	4.6	16.6
Hypersthene	50.2	11.0
Biotite	7.3*	3.8*
Amphibole, secondary	16.1	Very little
Magnetite+ilmenite	1.4	2.4
Pyrrhotite	0.2	0.2
Rutile	0.2	None
Total	100.0	100.0

* A special case. Generally there is more biotite in the quartz-norite than in the normal norite.

By the aid of the seven analyses stated above we may calculate the mean composition of the four main groups of rocks occurring in the field. They are as follows:

	Olivine-bearing Rocks	Marginal Zone of Normal Norite	Central Field of Quartz-Norite	Aplitic Granite Dikes
SiO_2	41.53	50.80	55.90	72.20
TiO_2	0.10	0.44	0.45	0.39
Al_2O_3	5.29	16.99	17.50	14.22
Fe_2O_3	2.40	0.44	0.08	0.55
FeO	9.64	6.47	6.97	2.00
MnO	0.24	0.14	0.09	0.03
MgO	36.98	13.20	5.98	1.03
CaO	1.85	8.43	8.32	2.60
BaO	None	Trace	Trace	0.02
Na_2O	0.59	1.43	2.75	2.55
K_2O	0.49	0.60	1.50	3.78
P_2O_5	0.07	0.03	0.05	0.08
Vd_2O_3	.....	0.09	.....	.....
S	0.20	0.06	0.05	Trace
Cr_2O_3	0.08	0.09	None	.....

These variations are illustrated in the diagram of the differentiation processes (Fig. 3).

By measurement from the exact geological maps of the field we find the areal distribution of the main rock groups to be the following:

	km.²
Quartz norite	30.0
Normal norite	33.2
Olivine-bearing rocks	3.8
Total	67.0

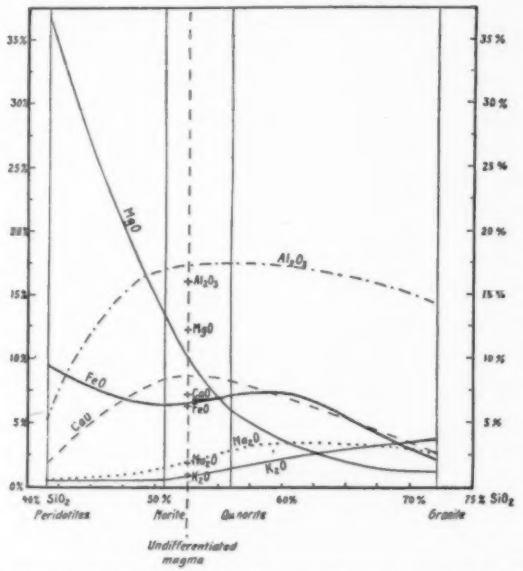

FIG. 3.—Differentiation diagram, based upon the mean composition of the main rock groups.

After the modifications necessary for the topographical irregularities, after recalculation to weight percentage, and after introducing the calculated quantity of the granite dikes, the proportion becomes the following:

	Weight Percentage
Aplitic granite	3.9
Quartz norite	31.3
Normal norite	57.4
Olivine-bearing rocks	7.4
Total	100.0

It may be noted here that these percentages are not proportional to the areal distribution of the rocks at the surface, because the quartz-norite and the normal norite without doubt are concentrically arranged throughout the field, so that any section through the center of the field will give the same image. Accordingly, their relative volume is with the greatest approximation calculated here after the formula for concentric spheres.

After the results given above, stating the quantitative proportion and the chemical composition of the main groups of rocks, we are in the rare and happy position to be able to state—with a fair amount of accuracy—the mean composition of the whole field, representing the original, undifferentiated eruptive magma. This composition is given in column o, in the table of analyses. The most remarkable feature is the very high magnesia content in connection with the relatively high silica content. It is an ideal norite magma.

The regular, stepwise development of the differentiation products is best seen from the norm calculations. Not only the chemical composition changes along definite lines, but also the composition of the individual minerals, especially the plagioclase and the rhombic pyroxene. Very remarkable is the regular change in the ratio $MgO^{mol}:FeO^{mol}$ in the silicates, decreasing markedly toward the salic rocks. The reason for this appears from what follows.

THE DIFFERENTIATION PROCESS

Starting with a study of the known forsterite-diopside-silica and the forsterite-anorthite-silica diagrams,[1] we learn that in the mean, undifferentiated magma of the Raana field, nearly without olivine in the norm, olivine will anyway be the first mineral to crystallize—beginning at the border toward the surrounding schists—and it will continue to separate out until the eutectical line olivine-pyroxene is reached. By further cooling, rhombic pyroxene crystallizes out at the same time as the *already formed olivine crystals are resorbed*.

If this process continued undisturbed, the final result would be an olivine-free rock, corresponding to the norm. However, we find

[1] See N. L. Bowen, *Jour. Geol.*, Vol. XXIII, suppl., pp. 20 and 29.

in the field, as stated above, a series of olivine-rich rocks all around the marginal zone of the eruptive body and of nearly the same age as the environing norite. These olivine rocks can only have been individualized during that period of the crystallization process when free olivine crystals were really suspended in the crystallizing marginal zone. It is obvious that even the slightest accumulation of these crystals at certain places would at once bring them in excess, and prevent them from being wholly resorbed.

Consequently, olivine would become a part of the norm composition at those places. We may conclude, therefore, that such an accumulation of olivine crystals has really taken place. That gravity separation has not played a prominent part in it is obvious from the distribution of the olivine rocks. We are forced to conclude that convection currents and other movements in the magma have been able to bring about such an accumulation, possibly also a conglutination of already formed crystals.

The explanation is confirmed by two facts: First, in all the olivine rocks the olivine crystals are surrounded by resorption rims, proving that resorption has been going on, but stopped at a certain point. Secondly, the olivine crystals in all these fields have nearly the same proportion, Mg_2SiO_4:Fe_2SiO_4, quite independent of the quantity of olivine, and consequently have all separated out from a uniform magma.

We get a natural explanation of the varying quantities of plagioclase and pyroxenes in the olivine rocks and of their "swimming" character in the norite magma.

After the termination of the resorption period and the consolidation of the olivine rocks, the rest of the magma in the marginal zone should obviously be expected to have become poorer in magnesia and richer in silica than the magma of original composition in the still fluid central part. Field observations teach us, however, that the olivine-free norite in a very thick marginal zone has a more basic composition than the central part.

To explain this, we might think of compensating currents in the magma prior to the resorption period, which in combination with the resorption of some of the olivine might produce this basic

composition. Chemical calculations, however, show this to be impossible, and the differences in the composition of the plagioclase point in the same direction.

We might also consider another sort of differentiation, according to which the marginal zone of the massive represents the mean, original composition of the magma, intruded by younger femic and salic differentiation products. The evident field observations, however, contradict such a supposition also.

Here, therefore, the squeezing theory, as developed by N. L. Bowen (*loc. cit.*), turns out to be a very natural and obvious explanation.

It must be remembered that the process takes place under orogenic pressure. While the segregated crystals are only suspended in the magma, the pressure is static and has no influence on the differentiation. From the moment when the outmost shell forms a fixed crystal mesh, this shell has eventually to take up the mountain pressure, but, of course, at first is not able to do so. The pressure then will be dynamic. Following Bowen, this stage is supposed to occur when about 80 per cent of the mass is crystalline and only 20 per cent liquid.

As the volume of the magma is diminished by cooling and still more by crystallization, the outer shell will be compressed and its remaining interstitial liquid squeezed out. At that advanced stage of crystallization, this liquid will contain plagioclase, richer in soda, and pyroxene, richer in iron and lime than the already segregated crystals, moreover eventually potash-feldspar, free quartz, and magmatic water.

These components accordingly will move, and the direction of movement will be inward from the zone of dynamic into the zone of static pressure, because in the crystallizing zone with still static pressure the diminishment of volume will have the effect of releasing the pressure.

It is important to note that the process is here not supposed to be a squeezing for a long distance through a crystal mesh. Probably it is mainly a differential movement, restricted to the narrow transition zone, which moves inward at the same rate as the crystallization proceeds.

"The wave of crystallization is followed by a wave of squeezing." Continually the squeezed material will mix with the more fluid magma inside, which gradually becomes more acid.

The next step is the abrupt transition from the normal norite of the marginal zone to the quartz-norite of the central part. This is very easy to explain. It represents the stage when the outer, solid shell has grown sufficiently thick and strong to resist the compressing forces. From that moment no more compression and no more squeezing takes place. The remaining magma crystallizes quietly without further differentiation to a uniform quartz-norite, carrying a little free quartz and orthoclase, more acid plagioclase, and much biotite on account of enrichment of the magmatic water.

Of course, the contraction or the release of pressure continues as the crystallization proceeds, and finally results in a general formation of fissures in all directions, when the resulting stresses have grown sufficiently strong.

This fissuring obviously occurred at a stage when the quartz-norite was consolidated, with exception of the very last interstitial liquid, containing a considerable proportion of magmatic water and mineralizers. The liquid was drained into the fissures, forming aplitic dikes of soda-rich granite. This last separation is obviously not due to squeezing; but whether the liquid was really sucked out into the fissures or driven out by the pressure of the enriched gaseous mineralizers is difficult to tell. At any rate, there resulted a direct connection between these dikes and the last consolidated minerals in the quartz-norite, producing the slightly blurred contacts mentioned above.

Also in the marginal normal norite, clefts were formed at this period and filled with the same dikes of granite. Here they have razor-sharp contacts because the marginal rock at that time was completely solid.

The mineralizers once more separated out, carrying with them much potash and silica and giving rise to veins of pegmatite and pure quartz, both rich in tourmaline.

From the foregoing we see that the theory as modified covers all the observed facts. It is beyond doubt that the differen-

tation proceeded quite *in situ* and is confined to the crystallization period. Further we have learned that the squeezing differentiation gives results which in many respects are similar to those of gravitative separation. In the one case the liquid is removed from the crystals, in the other case the crystals from the liquid.

There is only one point left which cannot yet be explained in detail: how some of the primary olivine crystals could be brought to accumulate or conglutinate at certain places. On this point, therefore, we can only state the fact and remark that any supposition of immiscibility of olivine with the rest of the magma, resulting in the formation of fluid drops of olivine, would not help us, but be in opposition to several of the above-stated facts.

As will easily be seen, the special differentiation type of Raana is not apt to occur very frequently. It presupposes the following conditions: (1) the crystallization must take place under lateral pressure; (2) it must take place completely *in situ*, in a closed room without supply of new magma during the process; (3) gravitative separation must not play a prominent part.

In the same district we meet a somewhat different type of squeezing differentiation, one which will prove to have a more general occurrence in orogenic folding zones. It occurs when the central part of the eruptive mass is not—as in Raana—protected against lateral pressure. A short statement of it is here added.

THE AMPHIBOLITE SERIES

As mentioned in the first part of this paper, in the folded mountain region there occur considerable quantities of femic eruptive rocks very intimately injected into the schists and completely recrystallized through dynamic metamorphism. They do not occur in so extensive individual masses as do the fresher rocks of the Raana type, but they are much more widely distributed. Chemically they have diabasic composition and differ from the corresponding rocks of the Raana field in carrying more iron in proportion to magnesia, more sodium, titanium, and phosphorus.

On account of the total parallelism of all eruptive injections in the district, direct observations of relative ages can generally not

be made. The amphibolites *might* be somewhat older than the Raana norites and accordingly have been subject to a longer period of dynamic metamorphism during the Caledonian folding. But the reason for the different degree of metamorphism might also be that the process has been able to act more severely upon these rocks on account of their lesser thickness and their very intimate injection in the surrounding schists—which show about the same degree of metamorphism—while the massives of the Raana type have resisted better.

The mineral composition of the ordinary amphibolites is: amphibole and acid plagioclase as the predominant minerals, more or less epidote or clinozoisite, quartz, leucoxene, and often garnet and biotite. None of the primary minerals are left.

The original basic plagioclase has been more or less albitized, producing plagioclases from albite to oligoclase composition, while part of the lime enters the epidote minerals. The original pyroxenes have been changed to amphibole, and it is noteworthy that while in the Raana field the uralitization has produced a nearly colorless amphibole of actinolitic composition, poor in aluminia, the metamorphic rocks contain common green amphibole, rich in aluminia.

The differentiation shows several features analogous to those just described from the Raana field, but also significant differences.

In many of the amphibolite zones we find a number of small bosses of serpentine rocks, very irregularly distributed. The dozens of such bosses observed nearly always occur within the amphibolite rock and are not separately injected into the schists. They are all of relatively small dimensions, rounded or lens-shaped, and sharply defined from the surrounding amphibolite. They obviously correspond to the peridotitic rocks of the Raana field, but are always completely metamorphosed to serpentine and talc minerals.

In numerous cases the amphibolite itself is nearly homogeneous, and without intermediate steps there is a wide gap over to soda-rich granites which occur nearly everywhere in intimate connection with the amphibolite series in such a way that there can be no doubt of their mutual relation as differentiation products.

Here the granite does not occur as crossing dikes, but as small lenses or bands arranged parallel to the schistosity of the amphibolites. In some cases they occur as separate sheets of considerable thickness in or at the border of the amphibolite. Only in rare cases, when the amphibolite has retained a more massive structure without marked schistosity, do they occur as numerous crossing, irregular stringers cutting the femic rock.

The contrast between the two rocks is still more marked than was the case in the Raana field on account of the great difference in chemical composition and the different degree of metamorphism. While the amphibolites are completely recrystallized, the granitic differentiates have retained much of their original structure, partly because they are somewhat younger, partly because the granitic mineral association has by far not the same tendency toward mineral readjustment under new conditions as is the case with the femic rocks.

These granites are characterized as soda-rich, but their composition may differ somewhat. Sodium may be quite predominant among the alkalies, the rock becoming a *Trondhjemite* as described by V. M. Goldschmidt from the Trondhjem district farther south. By increasing potash they get a more granodioritic composition, up to a limit with about equal molecular amounts of soda and potash. In all cases they are poor in dark minerals and generally have aplitic structure.

They are distinctly different from the ordinary granites in the district, which occur as great independent eruptions, and where the potash is always predominant.

The chemical composition of the ordinary amphibolite and its granitic differentiate is seen from the analyses on page 719.

In some cases we meet intermediate rocks between the amphibolitic and granitic extremities, mainly of dioritic composition. The variations are never regular, but form "schlieric" or banded alternations in the schistose rock.

From the foregoing we have seen that the characteristic regular differentiation step between the normal norite and the quartz-norite in the Raana field has no correspondent in the amphibolite series. This is a natural consequence of the fact that here the

central part of the mass was not protected against the lateral pressure which prevailed during the whole crystallization.

The result of the differential squeezing during the crystallization period has therefore been the ultimate separation of the last consolidating constituents of the magma. During the continued pressure after crystallization of the main rock mass, this last residue has been squeezed into the already consolidated rock as

ANALYSES

	No. 8	No. 9
SiO_2	49.12	67.49
TiO_2	2.46	0.29
Al_2O_3	13.70	16.52
Fe_2O_3	1.95	2.33
FeO	10.67	0.34
MnO	0.18	0.03
MgO	5.19	0.88
CaO	11.02	3.43
BaO	Trace	Trace
Na_2O	2.58	5.76
K_2O	0.44	1.93
P_2O_5	0.22	0.50
S	0.19	0.10
CO_2	1.21	None
H_2O+	1.37	0.81
H_2O+	0.01	(0.05)
Total	100.31	100.41
+O for S	0.10	0.05
Total	100.21	100.36

CALCULATION OF THE NORM

	No. 8	No. 9
Quartz	3.36	19.74
Orthoclase	2.22	11.12
Albite	22.01	48.73
Anorthite	24.46	13.34
Corundum	.....	0.10
Σ sal	52.05	93.03
Diopside	17.51	.....
Hypersthene	18.17	2.20
Hematite	.....	2.24
Magnetite	2.78	.....
Ilmenite	4.71	0.61
Apatite	0.52	1.34
Pyrite	0.36	0.19
Σ fem	44.05	6.58
$MgO^{mol}:FeO^{mol}$	1.24:1	.....

KEY TO THE TABLE OF ANALYSES

No.	Petrographic Name	Symbol	Locality	Analyst
8	*Garnet-amphibolite*	III. "5. "4. "5	Björkaasen Mine	Olaf Röer
9	*Aplitic granite*	I " .4.2.4 "	Brugsaas	Naima Sahlbom

lenses, stringers, and bands of aplitic granite. Their ordinary arrangement parallel to the schistosity shows that this must have been partly developed already during the consolidation as crystallization schistosity.

The magmatic water and mineralizers with their dissolved substances seem to have taken their own path, having a more active power of motion contrary to the purely passive motion of the ordinary squeezed material.

They have given rise to replacement phenomena and formation of ore deposits, still younger than the aplitic granite.

GEOLOGIC RECONNAISSANCE IN BAJA CALIFORNIA

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During 1921, I spent several months in Baja California determining geologic relations of a large area, and as there is but little on record regarding the geology of this region, it is desirable to set forth such of my observations as appear to be of general interest. I journeyed with pack train from near Ensenada southward to beyond Comondu and later extended the reconnaissance to beyond La Paz as far as Todos Santos. Most of the observations were in the district between the high sierra and the west coast, but the peninsula was cross-sectioned near San Ignacio and Santa Rosalia, from Mulegé to La Purisima, and in the La Paz region (Fig. 1).

Most of my attention was given to the sedimentary rocks of Cretaceous and Tertiary age, but the limits and character of some of the crystalline rocks were ascertained. Many of the general relations are set forth in the cross-sections of Figures 2, 3, and 4.

PRE-CRETACEOUS

The lowest strata observed were schists and other metamorphic rocks, invaded by white, massive, coarse-grained granite. At most places this granite includes fragments of schist, and many clearly intrusive contacts were noted. The granite constitutes the high Sierra San Pedro Martir in the north central part of the peninsula, where one or two summits reach an altitude of about 10,000 feet. It also outcrops north of Ensenada, north of Santa Caterina, and in many high central ridges from latitude 29° 30′ to latitude 28°, and is prominent in the sierra at the lower end of the peninsula southeast of La Paz. I crossed the schists in several broad zones between Santa Caterina and Calmalli and noticed that a few miles

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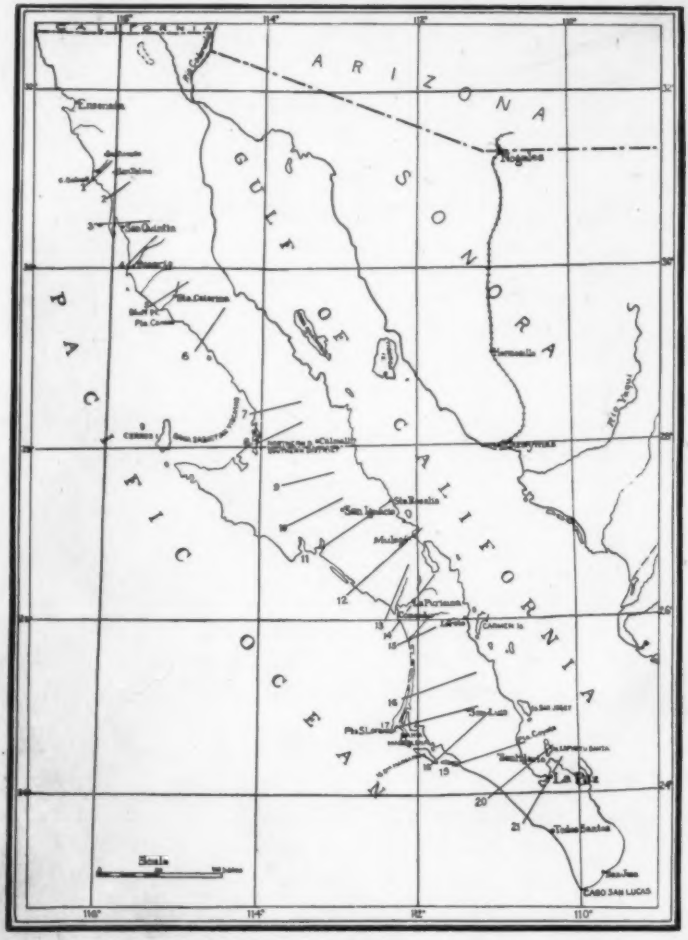

FIG. 1.—Map of Baja California showing principal shore features and settlements, and location of cross-sections in Figures 2, 3, and 4.

south of the latter place they are overlapped by younger sediments. They appear again in high ridges in Cerros Island and from Punta San Lorenzo to Isla Santa Margarita on the west side of Bahia

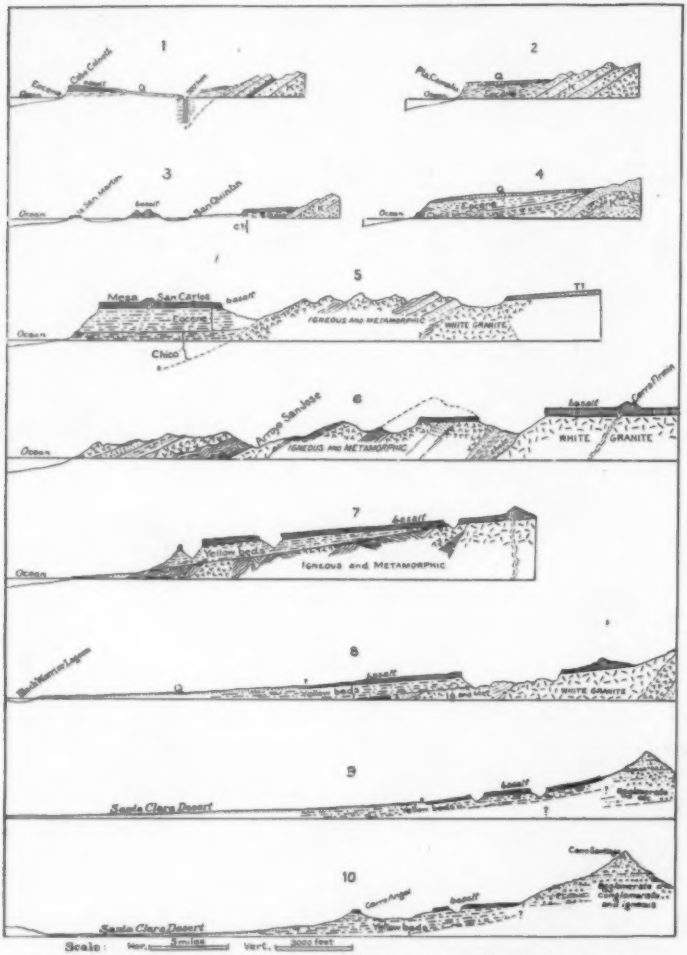

FIG. 2.—Sections across parts of northern and central Baja California
Q = Quaternary

de la Magdalena.[1] They also occur in the south end of the peninsula in the Triunfo mining district south of La Paz.

[1] According to J. Ross Brown, *Resources of the Pacific Slope*, San Francisco, 1869, p. 143.

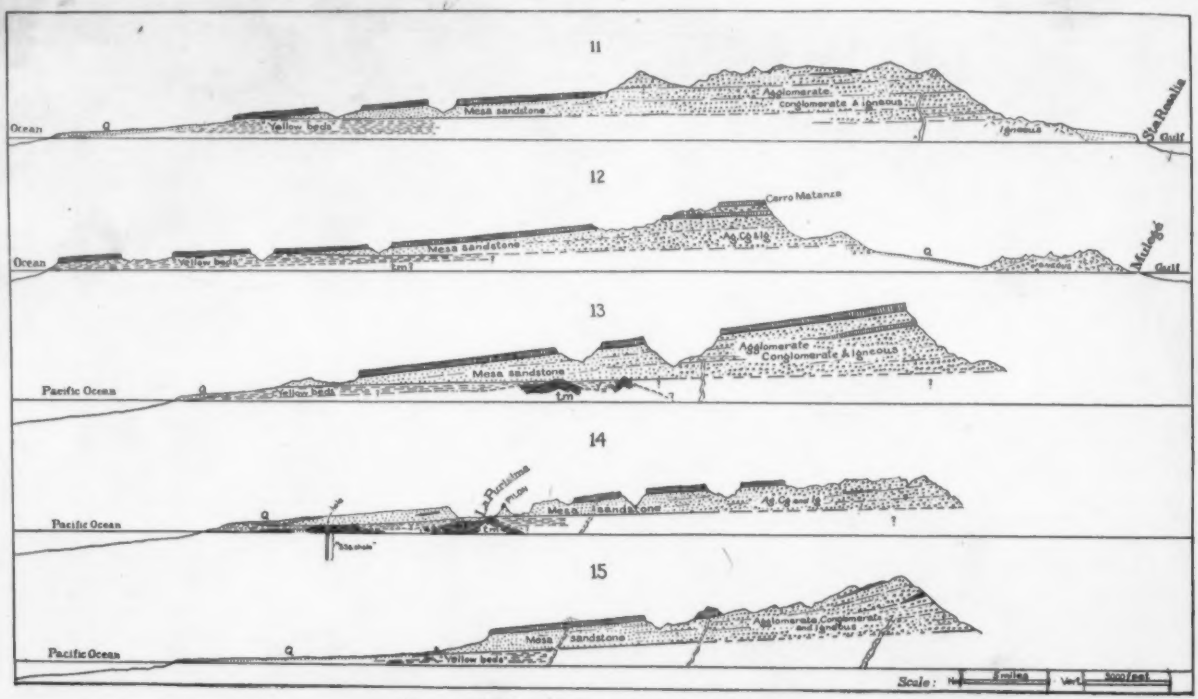

FIG. 3.—Sections across central Baja California.
Q=Quaternary

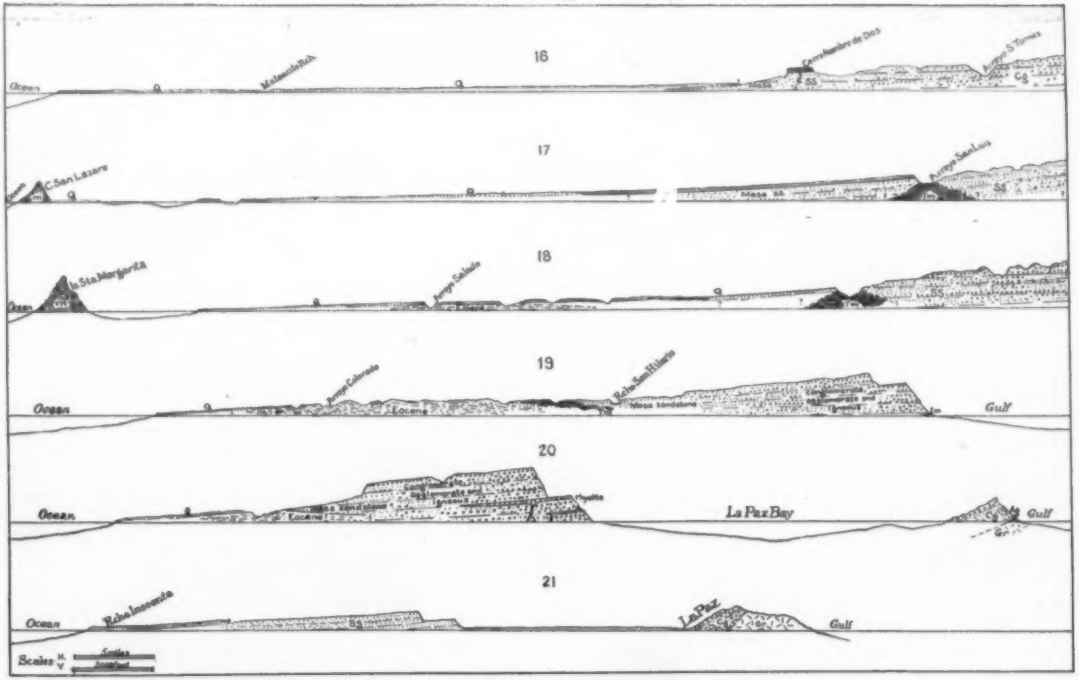

FIG. 4.—Sections across part of southern Baja California

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Lindgren[1] has given considerable information regarding schist and granite in the northern part of the peninsula; Gabb[2] noted some features observed on his trip north from La Paz; and Emmons and Merrill[3] described relations of the schists near the onyx quarries east of Santa Caterina.

I obtained no evidence as to the age of these granites and schists, but my general impression was that they were much older than Cretaceous. I did not observe any overlap by Cretaceous rocks, but I saw Tertiary deposits lying on or against them at various places. In the region east of La Paz, the granite appears to be the floor on which the Tertiary volcanic series lies. This relation is strongly indicated at Cabo Lobos on the east side of Isla Espiritu Santo where a separating fault appears hardly possible. A similar relation is indicated in Sierra Giganta, northwest of Loreto. The structural relations of the ridges of schists in Isla Santa Margarita and extending northward to Cabo San Lazaro is not known, and it is not unlikely that these rocks are the uplifted floor of the strata farther east.

Fig. 4.—Sections across part of southern Baja California

CRETACEOUS SYSTEM

General relations.—A large part of the peninsula is underlain by Cretaceous rocks which outcrop extensively in the central and northern parts. Two principal series are present, both of late Cretaceous age and separated by an uncomformity, the older series, of unknown correlation, having been uplifted, flexed, and cut by large igneous masses before the younger series, Chico, was deposited. The Chico beds were not observed in contact with the older series, and the principal evidence of the separateness of the two is the difference in attitude of the beds throughout the area and the fact that the older series is uncomformably overlapped by

[1] Lindgren, "Notes on the Geology of Baja California, Mexico," *Proc. Cal. Acad. Sci.*, Second Series, Vol. I (1889), pp. 173–96, and Vol. II (1890), pp. 1–17; and "Geology and Petrography of Baja California, Mexico," *Proc. Cal. Acad. Sci.*, Second Series, Vol. III (1890), p. 26.

[2] W. B. Gabb, *Geol. Survey of Cal.: Reports*, Vol II (1869), Appendix, pp. 1–20.

[3] S. F. Emmons and G. P. Merrill, "Geological Sketch of Lower California," *Bull. Geol. Soc. Am.*, Vol. V (1894), pp. 489–514.

the Eocene strata which lie with apparent conformity on the Chico beds. This relation is shown in the following section (Fig. 5).

These pre-Chico Cretaceous rocks consist of conglomerates, quartzites, tuffs, and agglomerates with large bodies of interbedded eruptive rocks. They are also cut by dikes and large stocks of igneous rocks of various kinds. In many localities the igneous rocks predominate over the sediments or pyroclastics, and in places there is much metamorphism. Unaltered or but little altered sandstone and shales appear in places, notably near old San Domingo Mission, 25 miles north of San Quintin, where they contain many large oyster shells, and in the Arroyo San José, 40 miles southeast of Santa Caterina. Limestone also occurs. It is conspicious north and northeast of the ruins of Mission San Fernando, 30 miles due east of Rosario, where the relations shown in the following sketch section (Fig. 6) are presented. The limestone is filled with fossil oysters of upper Cretaceous age. Part of the outcrop is shown in Figure 7.

FIG. 5.—Sketch section showing relations of Eocene and Chico beds to metamorphic and igneous rocks of Cretaceous (pre-Chico) age, near latitude 30°, west coast, Baja California. *a*, exposed overlap of Eocene beds.

These metamorphic Cretaceous rocks appear to extend as far south as latitude 28° 40′, and possibly the schists and other rocks,

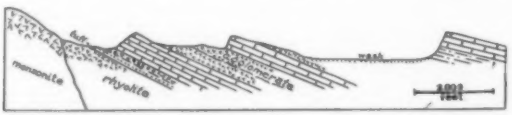

FIG. 6.—Sketch section showing relations of Cretaceous limestone north of the ruins of San Fernando Mission, 30 miles east of Rosario, Baja California.

although apparently of an older series and extending to Calmalli, may be metamorphosed Cretaceous sediments. Apparently they are so regarded by Bosé and Wittish in their brief statements regarding relations in the Northern District.[1]

[1] "Memoria de la Comisión del Instituto Geológico de México que exploró la región Norte de la Baja California," *Inst. Geol. de México, Perergones*, Vol. XIV (1913), pp. 307–533.

CHICO FORMATION

The upper part of the Chico formation (late Cretaceous) rises above sea-level a few miles north of Rosario, and it remains in view along the ocean bluffs and lower parts of the valleys of the Rio Rosario, Arroyo San Vicente, Rio San Fernando, and Arroyo Santa Caterina as far as latitude 29° 24′, a few miles southeast of Punta Canoas. The rocks are soft sandstone and shale of light-gray to buff color with round concretions at most places. Emmons and Merrill[1] noted the occurrence of Upper Cretaceous fossils at a point about 3 miles north of Santa Caterina Landing. Specimens collected from massive sandstone near sea-level and in calcareous layers 200 feet above were determined by T. W. Stanton as follows: *Arca breweriana* Gabb; *Baculites chicoensis* Trask; *Tessarolax distorta* Gabb; and *Inocerami*, not determinable.

FIG. 7.—Fossiliferous Cretaceous sandstone northeast of San Fernando Mission, twenty miles east of San Rosario, Baja California.

The fossils which I obtained in these beds at the Arroyo Hondo, 15 miles north of Rosario, were identified by Dr. T. W. Stanton as follows: *Rynchonella* sp.; *Ostrea* sp.; *Inoceramus whitneyi* Gabb; *Yoldia nasuta; Nemodon vancouverensis* Meek?; *Dentalium* sp.; *Gyrodes* sp.: *Anchura* sp.: *Cinulia obliqua* Gabb; *Baculites chicoensis* Trask; and *Baculites occidentalis* Meek. All these fossils are typical of the Pacific Coast Chico which is of Upper Cretaceous age.

Lindgren[2] has reported the occurrence of the Chico fossil, *Coralliochama orcutti*, in sandstones appearing in a small area among the volcanic rocks a few miles southwest of Ensenada.

[1] *Op. cit.*, p. 501.

[2] *Op. cit.*, p. 176.

TERTIARY SYSTEM

EOCENE

General relations.—I found that on the shore of the Pacific Ocean the earlier Tertiary deposits began at the mouth of the Rio San Vicente in latitude 31° 30′ and extended south to about latitude 29° 25′, south of Punta Canoas. In this area they underlie a narrow coastal plain mostly from 8 to 10 miles wide, but broadening to nearly 20 miles near latitude 30°. They lie on the Chico beds but to the east abut against the metamorphic pre-Chico rocks, and the termination of the crop to the north and south is due to the westward extension of the latter to the ocean shore. Throughout the area the strata dip at very low angles to the west, and local flexures are rare and slight. Some general relations are shown in sections 1–5, Figure 2.

The rocks are shales and sandstones mostly of light-gray to buff color, 1,200 feet or more thick near latitude 30°. To the south they contain fossils of the Martinez or Middle to Lower Eocene age, but in the region north of latitude 30° most if not all of the beds appear to be Tejon or Upper Eocene, although the lower formations may exist beneath the surface. There are prominent exposures along the lower parts of the valleys of the Rio Rosario, Arroyo San Vicente, Rio San Fernando, and Arroyo Santa Caterina, near Rosario and southward, and in bluffs along the ocean near Cabo Colnett and Punta Camalu and near Bluff Point and Punta Canoas, the two latter southwest of Santa Caterina. As shown in section 5, Figure 2, the thick succession of beds exposed in the bluffs along the ocean at Bluff Point is preserved by the heavy lava cap of Mesa San Carlos.

Fossils.—Fossils were collected at several localitities in the Eocene beds and kindly determined for me by Dr. Julia A. Gardner. On the shore of the Pacific Ocean, a mile south of the mouth of the Arroyo San Antonio, latitude 31° 05′, the following were found: *Cylichna* sp.; *Turritella* n.sp., cf. *T. uvasana* Conrad; *Amauropsis* sp.; *Leda* sp.; *Cucullaea matthewsoni*, Gabb?; *Cardium*, cf. *C. breweri* Gabb; *Cardium* sp.; *Tellina?* sp.; and *Semele* sp.

On the ocean shore a half-mile south of Colnett Creek, 5 miles southeast of Cabo Colnett, were collected *Omphalius* sp.; *Cardium*

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n.sp., cf. *C. quadrigenarium* Conrad. In the bluffs 5 miles east of San Quintin there were collected *Turritella* n.sp.; *Leda* sp.; *Tellina* sp., cf. *T. hornii* Gabb; and *Spisula* sp., cf. *S. merriami* Gabb. In the drift at the mouth of San Simon Cañon, 6 miles southeast of San Quintin, *Cardium cooperi* Gabb? was collected. These are all regarded as Tejon or Upper Eocene in age. The following fossils were collected from two horizons in the slopes about 5 miles northeast of Santa Caterina Landing: Upper beds, *Surcula* sp.; *Heterotoma gabbi* Stanton: *Turritella pacheococensis* Stanton?; *Turritella* sp.; *Natica (gyrodes)*, cf. *N. lineata* Dickerson; *Amauropsis* sp.; *Dentalium cooperi* Gabb?; *Leda* sp. 2; *Glycimeris* n.sp. aff. *G. veatchii* var. *major* Stanton; *Cucullaea matthewsoni* Gabb; *Ostrea* sp. ind.; *Pecten* sp.; *Pinna* sp.; *Crassitellites* sp.?; *Venericardia planicosta* Lamarck var.; *Phacoides* sp., cf. *P. diegoensis* (Dickerson); *Phacoides* sp.; *Cardium cooperi* Gabb?; *Cytherea* sp. aff. *C. hornii* Gabb; *Spisula* sp. The age of these is regarded as Upper Martinez or Middle Eocene.

From beds 200 feet lower were collected: *Cucullaea matthewsoni* Gabb?; *Ostrea* sp. ind.; *Anomia* sp.; *Lima multiradiata* Gabb; *Phacoides* sp. ind. The age of these is regarded as Lower or Middle Martinez or Lower Eocene.

Emmons and Merrill[1] reported fossils from rolled pebbles of impure limestone obtained along the beach of the south of Santa Caterina Landing "which had evidently fallen from the cliffs above, and from a bed of similar composition in place at what was assumed to be about 1,200 feet higher in horizon, at San Carlos anchorage (collected by Mr. A. E. Foote), 8 miles north of Bluff Point." These were determined by Dr. T. W. Stanton as follows: *Cardita planicostata* Lam., *Leda gabbi* Conrad, *Urosyca caudita* Gabb, and undetermined species of *Nucula*, *Pectunculus*, *Tellina*, *Turritella*, *Dentalium*, and *Crassatella*. These forms were regarded as Tejon (Upper Eocene).

EOCENE (?) WEST OF LA PAZ

Sandstones which appear to be of Eocene age outcrop in an oval area of about 200 square miles in the valleys of arroyos Liebres, Colorado, San Hilario, and Guadalupe, all west of San Hilario.

[1] *Op. cit.*, pp. 501–2.

Smaller exposures are revealed by the Arroyo Salado and its branches near Rancho Sauce, 35 miles west-northwest of San Hilario, and by arroyos Conejo and Datilari, 20 miles south-southeast of San Hilario (or about 40 miles due west of La Paz).

The rocks are light-gray sandstone, mostly soft, but with harder layers and hard concretions. Some argillaceous members are included and some of the sandstone layers have a greenish tint. In the extensive exposures on the Arroyo Colorado about Rancho Tepetate where dips are from 3° to 5°, the thickness is not less than 3,000 feet unless the strata are duplicated by faulting. The dips are somewhat steeper near Rancho Sauce where more than 2,000 feet of beds are exposed. One of the largest outcrops in this vicinity is just south of Rancho Santa Rosa where sandstone ledges extend along the banks of the arroyo for several miles. It is capped by late Tertiary or Quarternary conglomerate and limestone. In the valley of the Arroyo de los Liebres, ledges of sandstone and sandy clays are exposed in a wide area of low ledges and buttes which extend to, or nearly to, the mouth of the arroyo. All the dips are at low angles to the north.

FIG. 8.—Sandstone (Eocene?) on the Arroyo Colorado one mile below Rancho Tepetate, ten miles west of San Hilario, Baja California.

The exposures in the valley of the Arroyo Colorado extend from the junction with the Arroyo de los Liebres nearly to the mouth of the Arroyo Caracol. Prominent cliffs of the sandstone occur at

Rancho Tepetate and for some distance above and below that place (Fig. 8). Dips are all to the north or north-northeast at low angles. The outcrop of the formation extends up the Arroyo San Hilario to within about 4 miles of Rancho San Hilario where the top member is massive, pale buff sandstone with irony layers and many fragments of oyster shells. It dips north and apparently passes beneath the Monterey beds. There sandstones have yielded few fossils, but echinoid spines and foraminifera are abundant at Rancho Tepetate, and oysters and a shark's tooth near Rancho Santa Teresa all appear to indicate Eocene age. Evidently the exposures are due to a mound of the formation extending southeast and southwest with altitude sufficiently great in the region from the Arroyo Salado to the Arroyo Conejo for the strata to be revealed by erosion in the deeper valleys.

MIOCENE

Monterey beds.—In the vicinity of the oases of La Purisima and San Hilario I found small exposures of strata so closely resembling the Monterey formation of southern California that tentative correlation seems desirable. Outcrops extend along the Arroyo de la Purisima from 2 miles above tidewater to within 6 miles of La Purisima and a small one appears in the upper part of the latter village. Outcrops also extend along the valley of the Arroyo San Gregorio for a mile or more about 10 miles southwest of La Purisima, and smaller crops appear above Purisima Vieja and San José, respectively 15 and 20 miles northwest of La Purisima, and on the Arroyo San Raimondi, 35 miles northwest of La Purisima. The same beds appear in an area of 2 or 3 square miles a short distance west of San Hilario, and in small crops of steeply upturned beds appearing at intervals from a point a mile northwest of San Luis to a point 15 miles southeast of that place. The relations are shown in sections 13, 14, 17, 18, and 19, Figures 3 and 4. At most places the beds are more or less tilted and flexed, and various younger formations overlie them unconformably, as shown in Figures 9 and 10, although at several places where the strata are not flexed there appears to be gradation into the overlying "yellow beds."

The principal rocks of the Monterey beds are gray to pale-buff, fine-grained sandstone and sandy shale with abundant fish scales. They include interbedded diatomaceous deposits mostly from 1 to 3 feet thick and some thin layers of glassy silica from buff to black in color. More than 500 feet of beds are exposed along the Arroyo de la Purisima where for several miles the formation extends from 5 to 20 feet above the bed of the arroyo and there are many flexures.

The southernmost exposures in the Arroyo de la Purisima in the west end of the Big Bend about 2 miles above tidewater contain much fine, white diatomaceous earth interbedded in fine-grained, yellowish sandstone and compact shale with many fish scales. In

FIG. 9.—Flexures in the Monterey beds on the Arroyo de la Purisima, ten miles below La Purisima, Baja California.

this region the dips are to the west or southwest, so that higher beds rise as the valley is ascended. In about 3 miles the lowermost beds appear in the crest of a low anticline, and from these were obtained the following fossils, determined by Dr. Julia A. Gardner: *Scutella andersoni; Chrysodomus* sp.; *Turritella* sp., cf. *T. margaritana* Normand; *Vermetus* sp.; *Leda* sp.; *Arca*, cf. *A. medio-impressa* Clark; *Pecten*, cf. *P. crassicardo* Conrad; *Crassitellites* (*Crassinella*) sp.; *Cardium* sp. nov.; *Chione* sp.; *Cytherea* sp.; *Mecoma* sp.; *Solen* sp.; and some corals and bryozoa. The age is regarded as probably Vaqueros, equivalent to Lower Monterey. These lowest beds appear again in another small uplift a short distance north, beyond which the strata descend in apparent regular order showing extensive exposures in the banks of the arroyo as shown in Figure 9. Here the formation is overlain by conglomerate.

Yellow beds.—Under this title I shall group deposits of late Miocene age exposed extensively along the western slope of the peninsula from latitude 29° to latitude 24°. They are mostly soft, loamy sandstone and sandy clay of pale straw-yellow tint with local limy beds, the latter generally full of fossils. Some contemporaneous igneous rocks are included in places. The yellow beds have an aggregate thickness of 500 feet near the coast between San Ignacio and La Purisima, although at the latter place the amount is not more than 120 feet. As stated above, there is unconformity between this formation and the Monterey beds, only noticeable, however, where the latter are flexed; the overlying "mesa sandstone" is also unconformable, as shown in Figures 11 and 12.

FIG. 10.—Steeply tilted Monterey beds on east side of the Arroyo de la Purisima, six miles below La Purisima, Baja California.

The yellow beds are first noticeable in thin, scattered bodies lying on the metamorphic series near latitude 29°. Near latitude 28° 30′ they have the relations shown in section 7, Figure 2, having been preserved from erosion by a thick cap of basalt. This relation continues for many miles south, as shown in sections 8–15, although the floor of metamorphic rocks sinks out of sight a short distance south of Calmalli. In the La Purisima region and near San Hilario the underlying formation is the rather uneven surface of the Monterey beds. Probably the formation thickens considerably under the Santa Clara Desert, where doubtless it is underlain

by later Cretaceous rocks such as those reported to appear in the southern portion of the Santa Clara Mountains.

Local features.—About 150 feet of the yellow beds are exposed under the lava cap at Cerro Angel, 17 miles west of San Ignacio (see sec. 10, Fig. 2). The principal material is gray to pale greenish-yellow sandstone with beds of volcanic ash. There are extensive exposures about San Ignacio where the strata are capped by basalt, as shown in Figures 13 and 14.

FIG. 11.—Upturned "yellow beds" overlain unconformably by Mesa sandstone, six miles west of La Purisima, Baja California.

FIG. 12.—"Yellow beds" overlain unconformably by Mesa sandstone on Arroyo de la Purisima, five miles below La Purisima, Baja California.

The yellow beds in the exposures extending from the Arroyo Valle to beyond Rancho Quarente, about 40 miles south of San Ignacio, present a uniform succession, about 500 feet thick, of soft, yellowish sandstone and loam. The base is not exposed and the top is eroded. Some beds contain considerable clay, and others are nearly pure sand. The principal color is a pale greenish-yellow. A few thin layers of hard sandstone and conglomerate are included. A hard fossiliferous layer occurs in places in the middle of the beds exposed.

The yellow beds outcrop for many miles along the Arroyo San Raimondi (or San Miguel), 30 miles northwest of La Purisima, from a point a half-mile above Rancho las Tules to its mouth, with relations shown in Figure 16. Pale-yellow, loamy sands or soft sandstone prevail, and at several points, notably at Rancho San Antonio and near the outcrop of the Monetrey beds 6 miles southwest of Caije (a very small settlement 35 miles northwest of La Purisima), a basal limestone member is exposed filled with

FIG. 13.—San Ignacio, Baja California, from the south. High sierra in distance; later Miocene capped by basalt in middle distance.

FIG. 14.—Upper Miocene strata capped by basalt at San Ignacio, Baja California

fossils (not determined). Agglomerate and sheets of lava occur in the lower part of the formation in this valley, as shown in Figure 16.

In the valleys of the Arroyo Juanico and the Arroyo Mesquital, 20 to 25 miles west of La Purisima, the yellow beds are exposed in slopes and cliffs of considerable extent, overlain in part by lava and to the east by gravell beds at the base of the mesa sandstone. The principal material is soft, yellowish sandstone, in part containing some clay. The top beds have been eroded and the base is

not revealed, although probably not far below the bottom of the valleys.

In the Arroyo San Gregorio, about 6 miles southwest of La Purisima, the yellow beds are exposed lying on Monterey beds and overlain by mesa sandstone. They thin rapidly to the north where the surface of the Monterey beds rises rapidly. The yellow beds outcrop prominently again near Purisima Vieja, 10 miles northwest of La Purisima, exhibiting all the strata down to the richly fossiliferous limestone bed which occurs at the base of the formation near La Purisima. The following section is exposed in this vicinity. Probably Monterey beds are not far below the bottom of the arroyo at this place.

The stratigraphic relations of the yellow beds are extensively exposed in the Arroyo de la Purisima from near its mouth to a point

FIG. 15.—Section in the Arroyo San Raimondi northwest of La Purisima, Baja California. *a*, agglomerate; *m*, Monterey beds; *q*, Quaternary.

about 6 miles above La Purisima where the base of the overlying mesa sandstone crosses the canyon. The principal features are shown in the cross-section 14, Figure 2, and the columnar sections in Figure 17. For some distance near the 1,360-foot boring the yellow beds may either thin out or give place horizontally to a massive bed of conglomerate which lies on the Monterey beds; the precise relations are obscured by talus which breaks the continuity of the outcrops. The view, Figure 18, shows high cliffs 10 miles below La Purisima where the yellow beds include a massive member of impure limestone filled with fossils, apparently the same bed as the first one rising above tidewater several miles southwest (see Fig. 17, sec.1). This bed appears either to thin out or to give place to sandstone and agglomerate farther north near the drill hole. There are extensive exposures of yellow beds about La Purisima (see Fig. 19) with a basal member of limestone filled with

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fossils. This member is conspicuous in the bed of the arroyo a short distance below the village where it is crumpled in a series of small but closely appressed flexures. It also outcrops almost continously for several miles below this place, mostly in the bed of the arroyo. At two localities about 4 miles below La Purisima, small arches reveal the top of the underlying Monterey beds with contact clearly exposed. The yellow beds and this basal limestone disappear a short distance farther downstream or near the 1,360-foot boring, as shown in Figure 17. The precise stratigraphic conditions at this place could not be ascertained, but the basal limestone, at least, appears to abut against the old slope of a mound of Monterey beds, probably a local shore line.

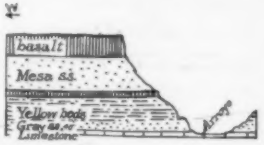

FIG. 16.—Section on the west side of the Arroyo San Gregorio opposite Purisima Vieja, ten miles northwest of La Purisima, Baja California, looking north.

The igneous rocks included in the yellow beds are the products of contemporaneous volcanic action, and it is not unlikely that to the east they grade into the lower part of the great succession of

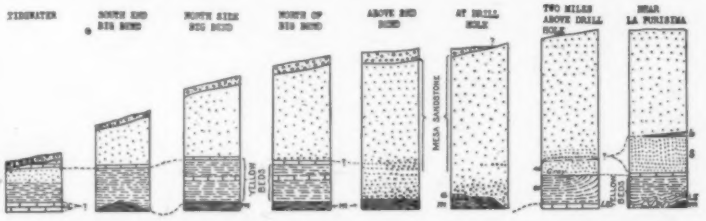

FIG. 17.—Columnar sections along the Arroyo de la Purisima, showing the stratigraphical relations of the yellow beds. *m*, Monterey beds; *a*, agglomerate; *ls*, fossiliferous limestone at base of yellow beds; *s*, massive sandstone at La Purisima; *b*, sheet of basalt in mesa sandstone.

agglomerates, etc., which constitute the base of the high sierra. In the valley of the Arroyo San Raimondi (or San Miguel), 40 miles northwest of La Purisima, there are many exposures of large bodies of agglomerate included in or displacing the upper members of the yellow beds (see Fig. 20). One notable outcrop is near the Rancho San Antonio, where the rocks have the relations shown in

Figure 15. Another similar mass is exposed in the Arroyo Valle, 8 miles west of Rancho San Antonio, and on the Arroyo Vaca, 50 miles west by north of La Purisima, there is an exposure high in the canyon walls showing the relations indicated in Figure 21. This section shows that the agglomerate was erupted during the time of deposition of the yellow beds and prior to the lava flow which now caps the mesas. A small amount of agglomerate lies on the Monterey beds in the Arroyo San Gregorio, 11 miles W. 10° S. of La Purisima, and also near the 1,360-foot bore hole on the Arroyo de la Purisima.

FIG. 18.—Yellow beds and overlying Mesa sandstone on the Arroyo de la Purisima, ten miles below La Purisima, Baja California. Massive fossiliferous bed near center.

Thin sheets of basalt are included in the yellow beds in the lower part of the canyons of the Arroyo San Raimondi and the Arroyo Caije. The relations of the old lava flows are well exposed just south of Caije and along the west side of San Juanico Bay, 7 miles due west of La Purisima. The exposure near Caije is due to a low dome, and here the lava is overlain by a 30-foot, soft, gray sandstone, a local member of the yellow beds. A thin sheet of basalt caps the yellow beds at Purisima Vieja, as shown in Figure 16, and halfway between that place and Poza Honda an igneous mass occupying the bottom of the valley was probably a vent from which this sheet was erupted.

Fossils.—The yellow beds contain fossils at various places which indicate later Miocene age, Carrizo Creek horizon. Possibly the sediments represent a still longer epoch. Fossils collected from the prominent limestone bluff at the head of tidewater at the mouth of the Arroyo de la Purisima were determined as follows by Dr. Julia A. Gardner, of the United States Geological Survey: *Scutella*

FIG. 19.—La Purisima from the south. Pilon in center is Mesa sandstone capped by basalt; slopes of yellow beds below. Lava-capped mesas in the distance.

FIG. 20.—Conglomerates, agglomerates, tuffs, and igneous flows near San Miguel, fifty miles northeast of La Purisima, Baja California.

gabbi Remond: *Terebra* sp., cf. *T. simplex* Carpenter; *Conus* sp., cf. *C. vittatus* Hwass; *Oliva* sp. aff. *O. angulata* Lamarck; *Oliva* n.sp. aff. *venulate* Lamarck; *Phos.* sp.; *Turritella* sp., cf. *T. cooperi* Carpenter; *Turritella* n.sp., cf. *T. ocoyana* Conrad; *Turritella* n.sp. aff. *T. goniostoma* Valenciennes; *Turritella* sp., cf. *T. ineziana* Conrad; *Cancellaria* n.sp., cf. *C. vetusta* Gabb; *Macron merriami* Gabb?; *Natica pablonesis* Clark?; *Chlorostoma* (*Omphalius*) sp.

aff. *C. dalli* Arnold; *Glycimeris* n.sp. (2); *Arca* n.sp., cf. *A. samuloensis* Osmont; *Arca* sp. ind.; *Ostrea veatchii* Gabb; *Pecten* (Pecten) *carrizoensis* Arnold; *Pecten* (*Lyropecten*) *crassicardo* Conrad; *Pecten* n.sp. A.; *Cardium* sp.; *Phacoides* sp.; *Mytilus trampaensis* Clark?; *Chione* sp. *Chione* sp., cf. *diabolensis* Clark; *Semele* n.sp. and *Balanus concavus* Brönn. The relations of this limestone are shown in the sections of Figures 1 and 2. Apparently it is at the base of the formation, and the same bed appears again along the arroyo a mile above the 1,360-foot bore hole and outcrops almost continuously to beyond La Purisima. In the vicinity of the latter place Dr. Kew collected the following fossils, determined by Dr. Julia A. Gardner, of the United States Geological Survey: *Strombus* n.sp.; *Turritella* n.sp.; *T.* n.sp., cf. *T. ocoyana* Conrad; *T.* sp., cf. *T. margaritana* Normand; *Calyptraea costellata* Conrad?; *Arca* sp. *Ostrea* sp. ind. *Pecten* n.sp.; *Venericardia* sp., cf. *V. cali fornica* Dall; *Chione* sp. *Chione* n.sp.: *Balanus concavus* Brönn—a Carrizo Creek fauna.

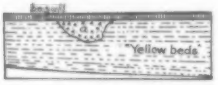

FIG. 21.—Section in east wall of canyon of the Arroyo de la Vaca, showing relations of agglomerate in the yellow beds.

The higher limy member occurring in a thick ledge near the middle of the yellow beds along the walls of the Big Bend and for some distance above it along the Arroyo de la Purisima, as shown in Figures 17 and 18, contain many fossils. A large collection was made from this horizon, but it has been misplaced in the National Museum in Washington. The basal limestone of the yellow beds outcropping in the bed of the Arroyo San Gregorio near Purisima Vieja yielded the following forms: *Purpura*, cf. *P. vaquerosensis* Arnold var.; *Turritella*, cf. *T. ocoyana* Conrad; *T.*, cf. *T. ineziana* Conrad; *T.*, cf. *T. margaritana* Normand: *Arca* sp. ind. *Pecten* sp., cf. *P. estrellanus* Conrad; *Pecten crassicardo* Conrad; *Pecten* sp., cf. *Pecten* n.sp., *Cytherea* n.sp. ind.—a Carrizo Creek fauna.

Only a few fossils were found in the extensive exposures of yellow beds north of the Arroyo Valle, 45 miles northwest of La Purisima. In a lower sandy member are abundant *Ostrea bourgeosii* Gabb and *Turritella*, cf. *T. jewetti*. At another place were collected, from the middle beds, *Chione*, cf. *C. elsmerensis* English and many specimens of *Tellina*, cf. *T. ocoides* Gabb. These fossils

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were determined by Dr. Julia A. Gardner, who regards them as probably Upper Miocene.

Fossils collected near the top of Cerro Angel, 18 miles west of San Ignacio, were identified as follows: *Oliva* sp.; *Turritella*, cf. *hoffmani* Gabb; *Calyptraea*, cf. *diegoana* Conrad; *Glycymeris* sp.; *Arca* sp.; *Pecten* n.sp.; *Pecten* sp.; *Dosiniaarnoldi* Clark; *Chione elsmerensis* English?; *Chione* sp.; and *Macoma vaulecki* Arnold. They are regarded as San Pablo or late Miocene.

These yellow beds outcrop extensively under the lava mesas about San Ignacio (see Fig. 14) and in the arroyo below that village. Fossil oysters are abundant in some of the layers.

Yellow beds similar to those of the La Purisima region overlie Monterey beds in the slopes east of Rancho Tepetate. The steeply uplifted strata just northwest of Rancho Platana include a richly fossiliferous limy ledge which yielded fossils of the same fauna as those occurring in the basal limestone member of the yellow beds in the Arroyo de la Purisima. The following were identified by Dr. Julia A. Gardner: *Strombos* n.sp. (same as one at La Purisima); *Turritella* n.sp. 1 and 2; *Codakia* sp.; *Cardium* sp. ind.; *chione* sp., cf. *C. fernandoensis* English; *C.* sp. ind. and *Psephidea?* sp.—a Carrizo Creek fauna. It is reported that later Miocene beds outcrop on the gulf shore near Cayote Point and Agua Verde Bay, doubtless coming up from under the agglomerate series, as shown in section 4.

From a bed in the base of the formation or not far below it, 8 miles northwest of El Pilon, were collected the following fossils: *Turritella* sp., cf. *T. margaritana* Normand; *Turritella* N. sp.; *Yoldia* sp.; *Ostrea* sp. ind.; *Mytilus?* sp.; *Modiolus?* sp.; *Pecten?* sp., *Chione* sp., cf. *C. fernandoensis* English and *Mactra?* sp.; determined by Dr. Julia A. Gardner who regards them as late Miocene or early Pliocene.

MESA SANDSTONE AND THE GREAT LATER TERTIARY VOLCANIC SERIES

Gabb recognized the fact that the widespread mesas of southern Baja California consist of a thick mass of west-dipping sediments and conglomerates. He named it the "mesa sandstone," and while he erroneously extended the application of the name to other

formations constituting mesas in the central and northern parts of the peninsula, the name may be useful in the southern part of the region until a more definite classification is practicable. I find that the formation presents two phases: a massive, gray sandstone, several hundred feet thick in the western portion of the mesa region, rapidly merging into conglomerates with thick bodies of agglomerate and tuff to the east. This relation is shown in sections 11–20, Figures 3 and 4, and is a most striking feature. The coarse sediments are in hard, massive beds, 4,000 feet thick in places, constituting the high sierra extending continuously southward

FIG. 22.—Mesa sandstone on the Arroyo San Andres, twenty-one miles south of Comondu, Baja California. Shows massive bedding.

from near latitude 28° to beyond La Paz. Sheets of contemporaneous igneous rocks are included and the succession is penetrated by many intrusions, notably in the Mulegé and Santa Rosalia regions. To the east it lies on schist, granite, etc., and to the west on sandstone of earlier Tertiary age. South of the latitude of La Paz the thickness diminishes, volcanic rocks are not present, and at Todos Santos the underlying rocks reach the shore of the Pacific Ocean. I did not observe its relations north of latitude 28°.

In the area of the great, lava-covered mesas extending along the Pacific slope past San Ignacio, La Purísima, and Comondu, the yellow beds are overlain by massive, gray, mesa sandstone. This sandstone is conspicuous in the walls of many canyons which

cut the mesa zone, notably in the arroyos San Raimondi (or Miguel), San Gregorio, De la Purisima, Comondu, San Benancio, San Andres, and Santo Domingo. The greatest thickness observed in this area is 300 feet; to the west the beds are thin out to nothing under the lava caps of the mesas, and to the east they merge into the great formation of detrital and volcanic rocks constituting the central sierra. This transition is well exposed in the Arroyo San Raimondi near the little pueblo of San Miguel, in the canyon of the Arroyo San Gregorio above Purisima Vieja, in the Arroyo de la Purisima above Huerta Vieja (a few miles above La Purisima), and it is also evident in the canyons from the Arroyo Comondu southward. The change to the east consists in the sediments becoming coarser and thicker, and probably overlying beds also are present under the great sheets of the basalt which cover the high mesas. Close scrutiny would probably reveal the presence of several formations in the sandstone series. A feature of this kind is clearly apparent about La Purisima where a harder, massive sandstone appears as a huge wedge in the other sediments (see Fig. 17). It thins out to the southwest, a mile or two below La Purisima.

The eastern extension of the mesa sandstone was not studied in detail, but was observed in various trips across the high sierra. The predominating rock is conglomerate in thick beds and consisting largely of bowlders of igneous rocks together with some quartzite. Sheets of lava, layers of tuff, and thick bodies of agglomerate are included. Some of the lavas are basalt, others are light-colored, more acidic rocks. To the east many intrusive masses are present. These are conspicuous west of Santa Rosalia, near Mulegé, east of Conception Bay, and southward past Loreto.

A fine exposure of mesa sandstone on the west bank of the Arroyo San Gregorio, 10 miles slightly north by west of La Purisima, shows the following strata:

	Feet
Lava sheet at top of mesa	00+
Sandstone, gray, massive, compact	60
Sandstone, white, soft	120
Bowlders and sand	40
Agglomerate, reddish in places	4
Yellow beds in bottom of the arroyo	30

Near Purisima Vieja, on the Arroyo San Gregorio, 12 miles northwest of La Purisima, a thin lava bed lies at the base of the formation (or in the top of the yellow beds, see Fig. 16), and a short distance above that place is a vent from which this lava flow probably came. Near San José, 7 miles farther up the same canyon, conglomerates predominate in the high canyon walls and two sheets of basalt are included. The later are well exposed in Arroyo Caije near Rancho Nombre de Marie, 25 miles south-south west of Mulegé. In the extensive exposures of the agglomerates and conglomerates near San Miguel on the Arroyo Raimondi (or Miguel), as shown in Figures 15 and 20, a thin sheet of trachyte is included in the succession. Near Rancho los Angeles in the same canyon the cliffs 500 feet high consist of coarse conglomerate, some beds being harder than others and consisting largely of bowlders of igneous rocks in gray sand. Below Rancho Mescal, a few miles above Rancho las Tules, underlying gray sandstone appears lying in yellow beds and in places on agglomerate which displaces the upper members of the yellow beds. These features are also well exposed halfway between Rancho las Tules and Rancho San Antonio. Not far below the latter place the basalt beds of the mesa sandstone thin out and the lava of the mesas lies directly on top of the yellow beds. The relations in this arroyo are shown in Figure 15.

Mesa sandstone appears at San Vicente, a ranch 5 miles southeast of La Purisima, where a fine spring issues from it, and is well exposed along the arroyos San Antonio and Pabellon 10–20 miles south of La Purisima. In the latter there are high bluffs of it at Rancho Pabellon and extending to beyond Coyote hole a watering-place as head of tidewater, 20 miles south-southwest of La Purisima. Here the rock is soft sandstone, in part pale greenish and yellowish. It is capped by caliche and conglomerate of Quaternary age which covers the adjoining mesas. The yellow tint may be due to a mixture of detritus from yellow beds which do not outcrop in this vicinity.

In the deep canyon of the Arroyo Comondu, near the village of Comondu, there are high walls of mesa sandstone capped by basalt of the lava sheets which cover the adjoining mesas, and there is also a cap of basalt at lower level, apparently a remnant

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of a sheet which flowed down the canyon when it had only about half its present depth. It is possible, however, that this lava sheet is included in the mesa sandstone, for such a relation is shown on the south side of the canyon 12 miles below Comondu, just above the mouth of the Arroyo Belamote. In that vicinity also there are some conglomerate members showing strong unconformity at base, and a few conglomeratic layers are included in the gray sandstone. It is probable that the mesa-sandstone outcrop extends down the Arroyo Comondu to Rancho San Andreta, near the mouth of the arroyo, where the following section is exposed:

Conglomerate.....30 feet, many fossils
Gray sand, pale greenish tint.....20 feet
Limy ledge, yellowish..... 5 feet exposed

Fossils collected from the basal bed in this exposure were determined by Dr. Gardner as *Turritella*, *Cytherea* and *Balanus* ?, and a *Chione* resembling *C. elsmerensis* English, probably Pliocene in age. This is the only paleontologic evidence that I obtained as to the age of the formation and it is not conclusive.

Extensive exposures of mesa sandstone are presented in the Arroyo San Benancio and the Arroyo San Andres south of Comondu, one of which is shown in Figure 22. The sandstone, conglomerate, agglomerate, tuff, etc., constitute cliffs and high canyon walls along the west side of the Gulf of California from Agua Verde Bay to Canyon de los Reyes. A section in the latter shows the following features:

GENERALIZED SECTION OF STRATA IN CANYON DE LOS REYES

	Feet
Soft, gray sandstones, some beds conglomeratic (top of ridge)	220
Rhyolite flow (bench-maker)	40
Soft, gray sandstone, several beds of conglomerate to the east	260
Conglomerate with bowlders of igneous and other crystalline rocks	40
Rhyolite flow (making wide bench)	30–70
Gray conglomeratic sandstone with agglomerate layers	200
Agglomerate, tuff, volcanic ash, igneous sheets. Bedding massive extends to tide-level	650
Total thickness	1,650

The thin sheets of rhyolite included in this section thin out to the south, but thicken considerably to the north, and the mass of agglomerate also thickens greatly in that direction. This series appears again in ridges passing just east of La Paz and on the islands of Espiritu Santo, Partida, and San Josef, where it consists of thick bodies of agglomerate, tuff, and eruptive rocks. The thinning and fining of the formation to the west is plainly visible in many canyons on the west slope of the sierra west and northwest of La Paz as far north as the Arroyo Santa Cruz near latitude 25° 20′. In this part of the peninsula the soft, gray, massive, typical "mesa sandstone" appears extensively in the highlands of the sierra as a component of the complex; but to the west, as the beds thin and fine, it becomes the dominant feature. It is exposed in the arroyos Conejo, Datilar, Guadalupe, 35–60 miles west of La Paz, and in the cliffs just below San Hilario; but at all of these places layers of pebbles are included and scattered bowlders occur. About El Pilon, 10 miles north of Hilario, it appears in many cliffs, some of which show limy layers. Farther north the conglomerate admixture increases notably in the vicinity of Rancho Jesus Maria, 35 miles north-northwest; but at the north side of Cerro Nombre del Dios, 6 miles southwest of that ranch, the gray sandstone contains only a few thin beds of conglomerate and widely separated bowlders. The westernmost exposure observed in this portion of the peninsula was on the Arroyo San Luis, 17 miles northwest of San Luis, where the sandstone is fine-grained and massive.

PLIOCENE TO POST-PLIOCENE

Along the wide belt of lower lands adjoining the Pacific south of latitude 26° 30′, there is a cover of sand and gravel with limestone members which doubtless include not only the Quaternary, but probably also a formation of Pliocene age. These deposits vary in thickness from a few feet to 200 feet or more, and they extend far up the slopes, and on the higher mesas they are probably represented by a thick cap of bowlders. The latter are especially well exhibited on the high mesas north and northeast of San Hilario and on the long sloping mesas crossed by the main trail north from San Luis. The wide, low plains of the Magdalena region are

covered by a deposit of sand of Quaternary age which to the south extends to the Arroyo Salado and beyond, and some distance up the slopes to the east. At Aqua Verde near Rancho Salado (latitude 24° 31′, longitude 111° 31′), underlying yellow sands with hard, limy ledges appear in a cliff 40 feet high. The section at this place is as follows:

	Feet
Gray conglomerate sandstone, which floors the adjoining low sloping mesa	15
Yellow, fine-grained sandstone somewhat harder beds above, and at base a wedge-shaped, hard, limy ledge with fossils	25

The fossils collected here were determined by Dr. Julia A. Gardner as follows: *Turritella* sp.; *Arca* aff. *A. microdonta* Conrad; *Mytilus* sp.; *Modiolus* sp.; *Periploma* (*Halistrepta*) *sulcata*, Dall?; *Tivela* n.sp.; *Chione latilamenosa*, A and M? *C.* sp.; *Metis* aff. *M. alta* Conrad and *Balanus* sp. "Age post-Miocene."

These yellowish beds extend for 3 or 4 miles up the Arroyo Salado and lie on the Eocene (?) sandstone. Probably their yellow color is due to material from the Monterey formation or yellow beds underlying them. They extend up the adjoining plateaus to an altitude of 500 feet or higher. Limestones of this formation are conspicuous in the Cerrito Flor de Melba, 60 miles west of La Paz, and on the walls of various arroyos from Datilar to Cuaño, as well as in cliffs along the ocean (60–40 miles west of La Paz). These limestones occur at several horizons, and they are highly fossiliferous at most places, but the fossils of the upper beds at least appear to be post-Pliocene. The dip is to the southwest at a low angle, and the beds extend far up the west slope of the sierra where they overlie the mesa sandstone.

THE GREAT UPLIFT

It has been found that much of the peninsula of Baja California has been uplifted out of the sea in very recent geologic times. Deposits of modern sea shells occur at many places in regions up to altitudes of 1,000 feet and they are reported as high as 3,300 feet. Old belts of sand dunes and shore lines are conspicuous far above

sea-level in several areas. Wittich[1] has presented many interesting facts relating to this subject with illustrations of shell deposits and shore features up to altitudes of 1,052 meters in a divide near Mission San Borja; this was as high as he ascended in his explorations.

The emergence has occupied a somewhat long time and may still be in progress. The shore erosion has been effected at various stages, although some of it may have been developed during the preceding submergence. The latter was apparently relatively transient, and most of the present configuration of the land was developed prior to this event.

[1] Ernesto Wittich, "La Emersion Moderna de la Costa Occidental de la Baja California," *Soc. Cien. Antonio Alzate (Mexico) Memoirs*, Vol. XXXV, pp. 121–44.

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